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A

TREATISE

ON THE

MICROSCOPE,

FORMING THE ARTICLE UNDER THAT HEAD IN THE SEVENTH EDITION OF THE

ENCYCLOPÆDIA BRITANNICA.

BY

SIR DAVID BREWSTER, K.G.H. LL.D. F.R.S.

VICE-PRESIDENT OF THE ROYAL SOCIETY OF EDINBURGH, AND CORRESPONDING MEMBER OF THE INSTITUTE OF FRANCE.

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TO

HENRY FOX TALBOT, Esq.

F. R. S., &c. &c.

My Dear Sir,

Having been requested to draw up a short and popular Treatise on the Microscope, for the Encyclopædia Britannica, I have endeavoured to give an account of the most important modern improvements upon that valuable instrument, and of the most interesting observations which have been recently made with it.

I could have wished to have enriched it with some account of the very curious discoveries which you have made with the Polarising Microscope, and which I had the advantage of seeing when enjoying your hospitality at Lacock Abbey; but as these required to be illustrated with finely coloured drawings, I trust that you will speedily communicate them to the public in a separate form.

In placing your name at the head of this little volume, I express very imperfectly the admiration which I feel for your scientific acquirements, and for the zeal with which you devote your fortune and talents to the noblest purposes to which they can be applied.

I am,

My Dear Sir,

Ever most faithfully yours,

D. BREWSTER.

Allerly, *Nov.* 16, 1837.

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TREATISE

ON THE

MICROSCOPE.

Microscope, from μικρος, a *small object*, and σκοπεω, *to see* or *examine*, is the name of a well-known optical instrument for examining and magnifying minute objects, or the minute parts of large ones. Dr Goring has, in his various ingenious works on the microscope, used the word *engiscope*, from εγγυς, *near*, and σκοπεω, *to see ;* but the old and venerable term is so associated with the history of optical discovery, and is so expressive of the application of the instrument, that we cannot consent to the proposed change.

Single microscopes in the form of glass globes containing water, were used by the ancients. Hemispheres of

glass, and afterwards lenses, were subsequently used, so that no person has pretended to claim the invention of the single microscope. The compound microscope, consisting of two lenses placed at a distance, so that the one next the eye magnifies the enlarged image of any object placed in front of the other, was invented by Zacharias Zansz, or his father Hans Zansz, spectacle-makers at Middleburg in Holland, about the year 1590. One of their microscopes, which they presented to Prince Maurice, was in the year 1617 in the possession of Cornelius Drebell of Alkmaar, who then resided in London as mathematician to King James VI.

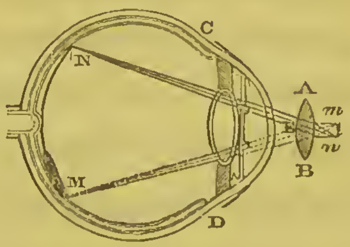
There is probably no branch of practical science which has undergone such essential and rapid improvements as that which relates to the microscope. It has become quite a new instrument in modern times, and it promises to be the means of disclosing the structure and laws of matter, and of making as important discoveries in the infinitely minute world, as the telescope has done in that which is infinitely distant.

CHAPTER I.

ON SINGLE MICROSCOPES.

A single microscope is one in which only one convex lens A B is used for magnifying objects. The object *m n* to be examined is placed before the lens A B, in its focus; and the rays which emerge from the lens after refraction by the eye C D are parallel, and therefore a distinct and enlarged image M N of the object *m n* is formed on the retina. The simplest form of the single microscope is when the lens is fitted into a rim of brass furnished with a handle, and the object being held in the left hand and the lens in the right, it may be examined with great correctness. If the convex lens is very minute, and has a short focal length, such as from the 10th to the 100th of an inch, it cannot be conveniently used in the hand,

Fig. 1.



and must therefore be placed in a firm microscope stand, having a shelf for holding the object, a screw or a rack and pinion for placing the object in the focus of the lens, and a lens or mirror, or both, for throwing light upon the object. In this form, however complex be its structure, it is still called a single microscope.

A single microscope, in order to have all the perfection which art can give, must consist of a *substance* perfectly homogeneous, like a fluid without double refraction, or any variation of density. Its *figure* ought to be that of a plano-convex lens, whose convex surface is part of a hyperboloid, in order to correct completely the spherical aberration. Its *surface* should be perfectly smooth and highly polished, so as not to disturb the perfection of vision; and the substance of which it is made should have the *lowest dispersive* power. As it is a great object to obtain high magnifying powers with as little convexity as possible, and a large aperture, substances with high refractive and low dispersive ones are the most suitable for single lenses, such as *diamond*, or *garnet*, which have no double refraction when well crystallized; or such as *ruby, sapphire, topaz*, &c. which have double refraction. As *fluor spar* has the lowest *dispersive power*, it might be used with great advantage when high powers are not wanted, and when the diminution of colour is an object.

Of all the substances we have named, fluids have pro-

perties best suited for single microscopes. They possess perfect homogeneity; their surfaces, when made into lenses, are perfectly smooth; and it is possible to mould minute drops of them into a form approaching to that of the hyperboloid. Their defect, however, consists in their not having a high refractive power, in their want of durability, and the difficulty of forming sufficiently minute lenses for producing high magnifying powers. These defects, however, especially the last, may be overcome by patience and experience; and in proof of this we may state, that we have succeeded in forming fluid lenses that were fully equal to the best sapphire lenses that have been executed.

In the present state of this branch of science, it would be unprofitable to detail the methods of producing microscopic globules of glass, given by Dr Hooke, Father di Torré of Naples, Mr Butterfield, or Mr Sivright; because when they are made after their methods, and in the most perfect manner which these methods will permit, they are of no value compared with lenses of glass when ground and polished to the same focal length.[1]

We shall therefore proceed to describe a single microscope when fitted up in the best form for observation.

---

[1] These methods may be found by the following references:—Hooke's Micrographia; Di Torré, Phil. Trans. 1765, p. 246, 1766, p. 67; Butterfield, Phil. Trans. 1678; Sivright, Edin. Phil. Journal, 1829, vol. i. p. 81.

Description of a Single Microscope.

The most essential part of this instrument is the lens or lenses, upon which the value of the microscope depends. The lenses are generally made of plate-glass, and should have focal distances varying from the $\frac{1}{10}$th to the $\frac{1}{30}$th of an inch. In order that the spherical aberration of these lenses may be the smallest possible, the radii of their two surfaces should be as 1 to 6; the surface whose radius is as 1, or the most convex side, must be turned towards the eye. The lenses, thus made, are then set in the centre or the lower surface of concave brass caps, a section of one of which is shown in Plate I. fig. 1.

The best mode of fitting up the microscope is that contrived by Mr Pritchard, which is represented in fig. 2, on a scale about one third of its real size. It is shown in an inclined position; but it may be used either in a vertical or a horizontal one, according to the convenience of the observer. The body of the instrument rests on a pillar *b*, supported by three legs, shown at *a*, and is connected with it by the clip *f*, being fixed by the pinching screw *f*. Within the tube *c* there slides a tube *h*, connected by a screw which passes through it to the triangular tube or bar *i*, carrying the arm *ij*, into which is placed the brass cap *j* which carries the lens. This lens is adjusted to the

distinct vision of objects placed on the stage *l*, by sliding the tube *h* up or down, and a perfect adjustment is obtained by turning the milled head *k*. The stage *l*, which carries the objects, is fitted into the triangular box *r* at the extremity of the stem, by means of two pins, and can be removed at pleasure. The spring slider-holder, for holding the sliders in which the objects are placed, is fixed by a bayonet-joint into the stage; and it may be used to hold stops or diaphragms for limiting the field of view. The tube above *f* represents an illuminator fixed to the slider-holder. Upon the tube *c*, two sockets *d*, *e* slide with sufficient spring and friction to keep them in their place. The socket *d* carries the reflector *d*, and the socket *e* carries the condensing lens, which is not inserted in the figure.

A section of the stem *rck* is shown in fig. 3, in order to exhibit the mechanism by which the adjustment is effected. Into the box *r*, screwed into the top of the stem, is fitted the triangular tube *ii'*, which carries the arm *ij*. In the lower end *i'* of this triangular tube is a small block with a fine screw working in it, the stem of which turns along with the milled head *k*, to which it is fixed. The upper end of a spiral spring, shown in the figure, bears against the block *i'* at the bottom of the triangular tube, while its lower end acts against a stop fixed within the sliding tube *h*. The method of managing, illuminating,

and examining opaque objects with this microscope is the same as that used in the achromatic compound microscope, in the drawing of which it will be more distinctly seen.

The preceding instrument of Mr Pritchard's is intended for general purposes; but as the dissection of botanical and other objects is now a leading object with naturalists, we shall add an account of another microscope, constructed by Mr A. Ross, with much skill, for Mr W. Valentine of Nottingham, the parts of which are given in considerable detail.

A perspective view of this microscope is shown in Plate II. fig. 4. It is supported on a closing tripod, *aaa*, whose feet can be folded together, and are made of hard bell-metal, prevented from springing by edge bars, as seen on the left-hand foot. A firm pillar, which rises from the tripod, carries the stage *x*, which is fixed on brackets, to give a steady support to the hands of the operator. A capital, *e*, fixed to the top of the tube by three screws, has in its axis a triangular hole, into which is fitted the triangular tube *f*, the lower end of which passes through another similar triangular tube in the piece *gg*, fixed to the tube. This triangular tube is made to slide up and down by a fixed screw, *i*, which is wrought by a large milled head, *o*, which is most judiciously placed at the base of the pillar. At the top and bottom of the triangular tube, at *g*, and

near *r*, are fitted two pieces, with triangular holes through them for receiving the triangular bell-metal bar *ss*, which moves up and down in them. This bar carries the arm 10 with the lenses. It is moved up and down, so as to adjust the lenses to distinct vision of the objects on the fixed stage, by the rack and pinion *t*, when a quick adjustment is required; but when a slow and nicer adjustment is wanted, it is effected by the milled head *o*. A slit, *uv*, is made in the shaft of the pillar, to allow the neck of the small milled head *t* to move up and down; for when the screw is in action by the large milled head *o*, the triangular tube and the bar move together. The triangular bar is perforated at both ends, the upper perforation for receiving a conical pin, and the lower for admitting the adjusting screw to preserve the length of the bar. The piece *w* is removed from the side of the pillar, to show the bearings of the pinion *t*, which are attached to the triangular tube. The bar moves $1\frac{1}{2}$ inch, and the tube $1\frac{1}{2}$, so that we can command an elevation of 3 inches. At the ingenious suggestion of Mr Solly, the screw *i*, moved by the milled head *o*, has fifty threads in an inch, and the milled head is graduated into 100 parts, for the purpose of measuring the thickness of any vessel or other object in the direction of the axis of vision. For this purpose the upper surface of the body is brought into distinct vision; the division at which the index or pin of the tripod stands is then observed; and the

under surface being in like manner brought into focus by turning the milled head *o*, the division is again observed. The number of divisions, which are each 5000ths of an inch, between these two numbers, *will indicate*, according to Mr Valentine, *the space through which the lens has passed, which is the diameter of a vessel.*[1]

In this microscope, different parts of an object may be brought into the field, either by moving the stage or the lens, a very important requisite in a microscope used for the purposes of discovery. With this view, the large stage *x* is formed of three plates, the lowest of which is fixed to the pillar by the ring 1; and, to make it bear the weight of the hands, it rests upon the strong brackets 2, 2. The under side of this plate is shown in fig. 6; the middle plate, fig. 7, contains two pair of dovetail slits, 3, 3 and 4, 4, the widest orifice of each being on opposite sides of the plate. The dovetail pieces in 4, 4 screw into the up-

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[1] This is not the case, as the refraction of the light issuing from the lower side of the vessel or object is not considered. The right mode is, after having observed the upper surface of an object lying upon glass, remove the object, and observe the divisions when the surface of the glass is seen distinctly: the difference will be the true thickness. Mr Samuel Varley is said to have constructed an instrument on this principle for measuring the thickness of foci of lenses; but unless he removed his lens after observing the first surface, his results must have been all erroneous.

per side of the upper plate, fig. 8, Plate III., the points of the screws being shown at 4, 4 in that figure, while the dovetail pieces in 3, 3 are secured to the upper side of the under plate by the screws 3, 3, fig. 7. The plates are thus moved diagonally, and at right angles to one another, by the adjusting screws 7 and 8, fig. 8. One of the screws, with its ball and milled head, is shown in fig. 9. In the adjusting screw 7, the ball is placed in spring couplings, and fastened to the under side of the upper plate. These screws are judiciously placed, one on each side of the pillar, that the hand may reach them easily and not intercept the light. By turning first one screw, and then the other, or both at once, any part of the object may be brought into the field.

The arm for holding the lenses is shown at 10, in fig. 1 and fig. 10. A conical pin projects from underneath, and fits into a hole made down the triangular bar, as shown at 9, fig. 8. The lens will therefore have a circular movement in a horizontal plane, and it may be placed at any point in this plane by the action of the rack and pinion at 10. Hence the most complete adjustment can be obtained without any motion of the stage.

The elevated stage for holding the objects is shown at 11 in fig. 4 and 8. A tube, 12, fig. 11, screws into the upper plate, and upon this fits the tube 11, carrying the finger spring, shown in fig. 4. Objects of different thickness are thus kept down upon the plates by the pins sliding in

the small pipes. An elevated stage is shown in fig. 12, for viewing the sides of objects without disturbing them. A condensing lens, fig. 13, slides into the sockets 5 or 6; and fig. 14 shows the pincers, to be applied in the same manner.

The large reflector above *a*, fig. 8, may be removed, and any other illuminating apparatus substituted. That of Dr Wollaston is shown in fig. 15, at 19. The handles 18, 18 serve to move the lens up and down in the tube.

The mode of attaching the body of a compound microscope is shown in fig. 16. For this purpose the arm 10, fig. 4, is withdrawn, and the conical pin 20 is made to fit in the same hole in the triangular bar.

Mr Valentine informs us, that with this instrument he can dissect under a lens $\frac{1}{20}$th of an inch focus.

Having recently had occasion to examine one of Mr Ross's microscopes, with achromatic object-glasses, we were surprised at the beauty and distinctness with which it exhibited the most difficult test-objects. We have never indeed seen any instrument superior to it.

As the stand and apparatus now described may be used along with all single microscopes, and also with what are called doublets and triplets, we shall now proceed to give an account of the various improvements which the single microscope has undergone.

Single Microscopes made of Precious Stones.

The low refractive power of glass rendered it necessary, when high powers were wanted, to use lenses with very short foci, and consequently with very deep curves and very small diameters, so as to admit only a narrow pencil of light into the eye.

Sir David Brewster was the first person who pointed out the value of using other materials for the construction of lenses; and he remarked, that no essential improvement could be expected in the single microscope, unless from the discovery of some transparent substance, which, like the *diamond*, combines a high refractive with a low dispersive power. Having experienced the greatest difficulty in getting a small diamond cut into a prism in London, he did not conceive it practicable to grind and polish a diamond lens,[1] and therefore did not put his opinion to the

[1] Mr Pritchard informs us (see *Edinburgh Journal of Science*, No. 1, new series, p. 149, July 1829), that Messrs Rundell and Bridge of Ludgate Hill had, at the time when Mr Pritchard began his experiments, many Dutch diamond-cutters at work; and that the foreman, Mr Levi, with all his men, assured him, *that it was impossible* to work diamonds into spherical lenses. The same opinion, he adds, was also expressed by several others, who were considered of standard authority in such matters. When Mr

test of experiment. He got two lenses, however, executed by Mr Peter Hill, an ingenious optician in Edinburgh, the one made of ruby, and the other of garnet; and these lenses he found to be greatly superior to any lenses that he had previously used.

Dr Goring, whose zeal and success in the improvement of microscopes has not been surpassed, directed the attention of Mr Pritchard in 1824 to the passages in Sir David Brewster's Treatise on New Philosophical Instruments, respecting the value of the precious stones for single microscopes; and having immediately seen their full force, it was agreed that they should undertake to grind a diamond into a magnifier.

Diamond Lenses.

The history of this attempt is so interesting, that we must give it in Mr Pritchard's own words:—" For this purpose," says he, " Dr Goring forwarded me a small brilliant diamond to begin upon; and it was proposed to give

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Pritchard had, contrary to the expectation of many, succeeded in finishing his first lens, it was examined by Mr Levi, who expressed great astonishment at it, and added, that he was not acquainted with any means by which that figure could have been effected.

it the curves that in glass would produce a lens of a twentieth of an inch focus, with the proportion of the radii of their surfaces as *two* to *five*. This stone I ground with the proper curves, and polished the flatter side, contrary to the expectations of many whose judgment in these matters was thought of much weight, who predicted that the crystalline structure of the diamond would not permit it to receive a spherical figure. When thus far advanced, fate decreed that I should lose the stone, and my only consolation was, to discover afterwards, that, had it been completed, its thickness and enormous refractive power would probably have caused the focus to fall within the substance of the stone.

" Having, however, in this experiment proved the possibility of working lenses of adamant, I set about another, and selected a rose-cut diamond, in order to form it into a plano-convex lens, and thereby save a moiety of the labour.

" In the progress of working this stone, the heat generated by friction, in the course of the abrasion of the diamond, was perpetually melting the cement (shell-lac) by which the flat side was affixed to the tool, and compelled me to seek some means by which it might be prevented. After several trials, I found, that when a portion of finely powdered pumice-stone was mixed with the shell-lac, the cement was much stronger, and less liable to melt, than any other similar substance.

"On the first of December 1824 I had the pleasure of first looking through a diamond microscope, and it was doubtless the first time this precious gem had been employed in making manifest the hidden secrets of nature. A few days after, I had polished it sufficiently to put it into the hands of Dr Goring, who tried its performance on various objects, both as a single microscope and as the objective of a compound. He states in a letter addressed to me, dated 3d January 1825, 'that it has shown the most difficult transparent objects I have submitted to it;' and again, 'I can clearly perceive the amazing superiority it will possess when completely finished.' I must, however, inform my readers, that we discovered in this state various flaws in the stone, in consequence of which we abandoned all thought of completing it. In this condition the project remained for about a year, when I determined to resume my attempts; and having worked several stones into lenses, I at last succeeded in obtaining a perfect one. In the course of these labours, a new though not unexpected defect appeared in several lenses, which would have subverted the whole scheme, had not the first diamond lens been free from it.

"These lenses, instead of giving a single image like the first, gave a double or triple one. This rendered them utterly useless as magnifiers, and made the defects of soft and hard parts in the same stone, and the small cavities in

others, of comparatively trifling consequence. The images exhibited in such lenses overlapped each other, but were never entirely separated, though the quantity of overlapping varied in different specimens.

"It was now evident that these defects arose from polarisation, though this stone is described as 'refracting single.' I subsequently learned from Dr Brewster, after I had overcome these obstacles, that this property of the diamond had been observed by him, and an account of it given in the Edinburgh Philosophical Transactions.[1] On referring to his paper, it appears Dr Brewster found that some stones 'polarised in particular *parts*, while other *portions of the same stone were quite free from any trace of polarity*,' and thus perfectly adapted to our purpose, as had previously been demonstrated in the first diamond lens.

"Notwithstanding these difficulties, and the consequent expense and labour they entailed on me before sufficiently experienced in working upon this refractory material with certainty, I have now the satisfaction of being able, by inspection *a priori*, to decide whether a diamond is fit for a magnifier or not; and have now executed two plano-convex magnifiers of adamant, whose structure is quite

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[1] Edinburgh Phil. Trans. vol. viii. p. 157, 1817. See also Geological Transactions, new series, vol. iii. p. 455; and London and Edinburgh Philosophical Magazine, vol. vii. p. 245.

perfect for microscopic purposes. One of these is about the twentieth of an inch focus, and is now in the possession of his Grace the Duke of Buckingham; the other, in my hands, is the thirtieth of an inch focus, and has consequently amplification enough for most practical purposes."[1]

Although it is quite certain that many if not most diamonds possess a doubly refracting and polarising structure, owing to their having been irregularly indurated when in a soft state, yet the separation of the images, arising from this structure, is not sufficient to account for the overlapping of the images observed by Mr Pritchard. In order to have this matter investigated, Mr Pritchard sent a bad diamond lens, with two or three images, to Sir David Brewster, who was for a long time perplexed with the difficulties which it presented to him. It occurred to him, however, to examine if the stone possessed a homogeneous structure, as he had observed in amber and gums, which are indurated in a similar manner, a variation in the refractive density capable of accounting for the imperfections of the diamond. In order to do this, he admitted a narrow beam of light into a dark room, and examined by this light the flat surface of the plano-convex lens of diamond with a hand microscope. After getting the diamond at the most favourable position, he was surprised

[1] Microscopic Cabinet, p. 107–111.

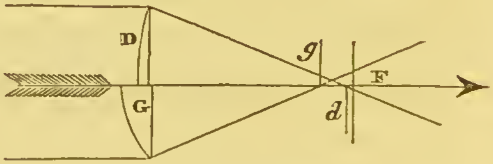
to see its whole surface covered with thousands of minute bands, some reflecting more and some less light, thus proving beyond a doubt that this diamond consisted of an infinity of layers of different reflective, and consequently refractive powers, from which arose all the irregularities of performance which it exhibited as a microscope. In this case the veins, as we call them, lay parallel, or nearly so, to the axis of the lens, so as to produce the worst possible effect; and had Mr Pritchard known previously that his diamond possessed such a structure, and made the axis of the lens perpendicular to the plane of these veins or laminæ, its performance as a microscope would scarcely have been affected by them. These observations will, we trust, induce opticians to use the diamond more frequently than they were disposed to do when they believed that its imperfections arose from its doubly refracting structure.

As the expense of the diamond, and the labour of working it, are very great, about fifty or sixty hours being necessary to complete a diamond lens with double convexity, it is of the greatest consequence to ascertain beforehand if the substance of the diamond is homogeneous, that is, free from difference of density or double refraction, and if it does not contain any small cavities. The best way is to examine the stone, by cutting two flat faces upon it, unless it is a *laske* or table diamond, which always has two flat faces; but this labour may often be avoided by exam-

ining it when plunged or held in a glass trough containing *oil of cassia*, the fluid which approaches nearest to it in refractive power. This will diminish all the refractions at the irregular surface of the diamond, and make any internal imperfections as easily seen as if its substance was plate-glass.

By comparing the indices of refraction of diamond and glass, it may be easily shown that the same magnifying power may be obtained with a *diamond* lens having its curvature with a radius of 8, as with a *glass* lens, the radius of whose curvature is 3; and as the spherical aberration increases with the depth of curvature or the thickness of the lens, a lens of diamond will bear a much larger aperture than one of glass before indistinctness of vision is produced. Mr Pritchard has given a very useful ocular representation of the relative value of a diamond and a glass lens. In the annexed figure, G is the section of a semi-lens of glass, and D the section of one of diamond, so placed that their principal focus F shall be at the same point. In the diamond semi-lens the marginal rays will intersect the axis at *d*, and in the glass semi-lens at *g*; the longitudinal aberration being *d*F in the *diamond*, and *g*F in the *glass* lens.

Fig. 2.



In order to obtain a numerical increase of these aberrations, Mr Pritchard computed them from the formula, and found that of the diamond lens to be $\frac{3}{7}$ths of its own thickness, that of the glass lens being $\frac{7}{6}$ths of its thickness; and by taking the thickness of the diamond lens to be 255, while that of the glass is 758, he obtained $\frac{3}{7}$ths of $255 = 108$, and $\frac{7}{6}$ths of $758 = 884$, and hence it follows that *the actual aberration of a* DIAMOND *lens is only about one ninth of the aberration of a* GLASS *lens* of the same power and aperture.

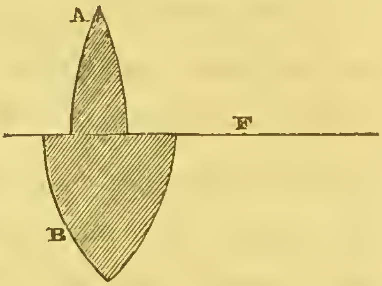
If we suppose the diamond lens to be ground on the same tool with the glass lens, so as to have the same curvature, the same thickness, and the same diameter, the longitudinal aberration of the diamond will be to that of the glass lens as 43 is to 117, or nearly one third of it; and if we suppose the focal length of both to be $\frac{1}{80}$th of an inch, the magnifying power of the diamond lens will be 2133, while that of the glass one will be only 800. In order that a lens of glass may have the same magnifying power as that of the diamond above mentioned, its focal distance would require to be only the 200th part of an inch.

The durability of the diamond lens is also another valuable property, which allows it to be burnished into a disc of metal, and taken out and cleaned without any danger of being scratched. In treating of microscopic doublets and achromatic microscopes, we shall have occasion to recur again to the diamond lens.

Sapphire Lenses.

The ruby and the sapphire are the same substance, differing only in colour. Mr Pritchard has, with his usual success, executed many lenses of sapphire, which, though inferior to those of diamond, are vastly superior to the best executed lenses of glass. When a double convex lens of sapphire and one of plate-glass are ground to the same focus, so as to have the same aperture and magnifying power, their relative curvatures are as 5 to 3, and their thicknesses as shown in the annexed figure, where A is the section of a semi-lens of sapphire, whose focus is at F, and B a section of a semi-lens of glass, having its focus at the same point. This figure points out in the clearest manner another advantage of using the precious stones in place of glass. In small lenses of glass, the thickness of the glass is such that there is no room between its anterior surface and the object for the admission of instruments for dissection, and not even for the thinnest plate of glass, so that it is impossible to use glass lenses of small foci in viewing objects placed in glass sliders. If the pre-

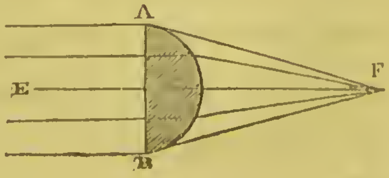
Fig. 3.



ceding figure represents lenses with a focus of $\frac{1}{30}$th of an inch, the distance of the glass lens B from F will be little more than $\frac{1}{60}$th of an inch, which is less than the thinnest glass.

In using the *sapphire* and *ruby*, or any precious stone which refracts doubly, such as *zircon*, *topaz*, &c. for lenses, we are exposed to a very serious defect, arising from the duplication of minute lines, in consequence of the double refraction of these crystals. In order to remedy this defect, the optician endeavours to cut the stone so that the axis of the lens may coincide with the axis of double refraction. This, however, is a difficult task; and, even if it were accomplished, we should not get rid entirely of the duplication of the images, as in all double convex lenses, as well as in plane convex lenses with the plane side turned to the object, the rays cannot pass through the lens in parallel directions, and therefore must suffer double refraction, however small. It may be reduced, however, to the smallest possible amount, and even to nothing, for pencils of rays diverging from a point in the axis, by making the lens plano-convex, and turning the plane side to the eye, as in the annexed figure, where rays issuing from F, and entering the eye parallel at E, must pass through the lens AB in parallel directions, suffering all their refrac-

Fig. 4.



tion at the first or curved surface of the lens. By adopting this form and position of the lens, we, however, lose more than we gain ; for the lens is placed in the position which gives a maximum spherical aberration. When the magnifying power is not very high, the residual double refraction is not injurious ; and in proof of this we may state, that we have in our possession a double convex lens of sapphire, executed by Mr Pritchard, which exhibits minute objects with the greatest beauty and precision. The only way, therefore, is to employ precious stones, such as the *diamond*, the *garnet*, and the *spinelle ruby*, which have no double refraction when their crystallization has been regularly effected.

Garnet and Spinelle Ruby Lenses.

The garnet is superior in its structure to the spinelle ruby, and the best and purest which we have seen is that which is brought from Greenland, and has a slight tinge of purple. We have used lenses made of this substance by Mr Hill, Mr Adie, Mr Blackie, and Mr Veitch, all of which exhibit minute objects with admirable accuracy and precision ; and we can state with confidence, that we have never experienced the slightest inconvenience from the colour of the garnet, which diminishes with its thickness, and consequently disappears almost wholly in very minute lenses.

Single Fluid Microscopes.

Mr Stephen Gray long ago proposed to construct single microscopes with drops of water, which he lifted up with a pin, and deposited in a small hole made in a piece of brass. The drop retained a sort of imperfect sphericity, and showed objects with some distinctness; but it is obvious that the very weight of the drop destroyed its spherical form, even if it had not been disturbed by minute irregularities on the circumference of the aperture in which it was placed.

Sir David Brewster long ago constructed fluid lenses in a different manner, so as to avoid the irregularities above mentioned. He placed minute drops of very pure turpentine varnish, and other viscid fluids, on plates of thin and parallel glass. By this means he formed plano-convex lenses of any focal length; and by dropping the varnish on both sides, he formed double convex lenses, with their convexities in any required proportion. By freeing the glass carefully from all grease with a solution of soda, the margin of these lenses was beautifully circular; and the only effect of gravity, which diminishes with the viscidity of the fluid and with the smallness of the drop, is to elongate the lower lens and flatten the upper one. These lenses

were found to answer well as the object-glasses of compound microscopes.

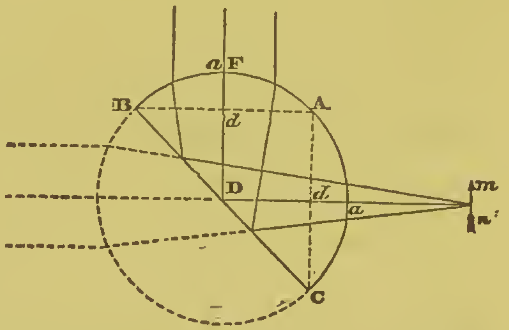
After experiencing the extreme difficulty of obtaining precious stones free of double refraction or difference of density, and from little cavities and imperfections, as well as the difficulty of giving their surfaces a perfect polish and a correct figure, Sir David Brewster has, we understand, recently made an extended series of experiments on the formation of minute fluid lenses, which should equal in power and distinctness those made of precious stones. The primary difficulty which was encountered in this attempt was that of depositing a sufficiently minute drop of fluid upon a surface of glass. This arose from two causes, from the difficulty of taking up on the slenderest fibre a minute globule of a fluid of any moderate tenacity, and the still greater difficulty of overcoming its adhesion to the fibre, and laying a portion of it on glass. The first of these difficulties he overcame by a suitable mixture of two fluids, and the second by a mechanical process. Having thus succeeded in obtaining lenses too small to be recognised distinctly by the eye, he next endeavoured to make their figure approximate to the hyperbolic form when the lenses were not of the smallest size, and the results which he obtained were far beyond his expectation. Some of these lenses preserved their perfection for more than a year, and if protected from dust might have been kept much longer. If

fluids could be obtained of a high refractive power, and not of a volatile nature, microscopes of extreme perfection might thus be readily constructed.

Catadioptric Lenses.

A single lens, by which light is both refracted and reflected, seems at first sight to be something paradoxical. Such a lens, however, which was proposed and used by Sir David Brewster, is shown in the annexed figure, where ABC is a hemispherical plano-convex lens, which, if we use it in the common way, will have a certain magnifying power; but if we use it as shown in the figure, it acts as a double convex lens of the same radius, and has consequently twice the magnifying power. Bisect the semicircle BAC in A, and join AB, AC. If we now place an object at *mn*, and look into the lens BA at F, we shall see by reflection from the surface BC the object *mn*, with the same distinctness and under the same angle as if we had placed the two lenses A*a* B*d*, A*a* C*d*, with their plane sides AB, AC together. Since the light is incident on the reflecting surface BDC at an angle of 45°,

Fig. 5.

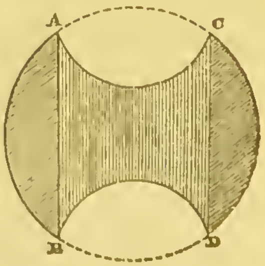


not a ray of it will be lost, as it suffers total reflection. The lens thus used has less spherical aberration than when used as a whole, ABC, and there is no error from imperfect centring. This lens may be used as the object-glass of a compound microscope; and it will be seen in another section that it possesses other advantages than those which have been mentioned.

The Grooved Sphere.

This lens derives its name from its having a deep groove cut round it in the plane of a great circle perpendicular to the axis of vision. Sir David Brewster was led to its construction by the doublet of Dr Wollaston, which will be described in another section. It consists of a spherical lens or sphere, with a deep concave groove cut round it, so as to cut off the marginal pencils, and thus give a wider field and a more perfect image. It is represented in the annexed figure, where ABCD is a sphere of glass, having the unshaded parts below AC and above BD cut away, in order to prevent rays that fall very obliquely from reaching the eye. The central thickness of the lens may be made so small as to render the spherical and even the chromatic aber-

Fig. 6.



ration almost insensible. As all the pencils pass through the centre, every part of the image will be equally distinct; a property possessed by no other lens whatever.

Mr Coddington,[1] who entertains a high opinion of the value of this lens, observes: "Besides all this, another advantage appears in practice to attend this construction, which I did not anticipate, and for which I cannot now at all account. I have stated, that when a pencil of rays is admitted into the eye, which, having passed without deviation through a lens, is bent by the eye, the vision is never free from the coloured fringes produced by eccentrical dispersion. Now with the sphere I certainly do not perceive this defect, and I therefore conceive that if it were possible to make the spherical glass on a very minute scale, it would be *the most perfect simple microscope*, except, perhaps, Dr Wollaston's doublet,[2] than which I can hardly imagine any thing more excellent, as far as its use extends, its only defects being the very small field of view, and the impracticability of applying it, except to transparent objects seen by transmitted light. Now the sphere has this advantage, that whereas it makes *a very good simple microscope, it is more peculiarly* fitted for the

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[1] Phil. Trans. 1830, part i. p. 69–84.

[2] This exception was needless, as the doublet is not a simple microscope, having two lenses placed at a distance.

object-glass of a compound instrument, since it gives a perfectly distinct image of any required extent, and that, when combined with a proper eye-piece, it may without difficulty be employed for opaque objects." We do not rightly apprehend the exact import of these observations. Mr Coddington distinctly asserts that the grooved sphere is the most perfect simple microscope, or the most perfect microscope with one lens; and yet he says in the next paragraph that it is only " a very good simple microscope," being " more peculiarly fitted for a compound instrument."

With regard to the difficulty of making it on a small scale, it is by no means great; for if we can grind and polish its two surfaces, we may readily excavate it round its margin. We have now before us a grooved sphere of garnet $\frac{1}{24}$th of an inch radius, executed by Mr Blackie: The focus is almost close to the lens, which in many kinds of observation is a great advantage, and its performance is remarkably fine.

It will be seen in our article on Optics, that when the refractive index of a sphere exceeds 2·000, its focus falls within the sphere. Hence a grooved sphere made of diamond is useless. When made with garnet, it is invaluable, and its focus is just thrown so near its surface, that the objects may be laid upon its surface, or pressed against it by a concave surface of the same radius.

Crystalline Lenses of Small Fishes.

The crystalline lens of minnows and small fishes may be taken out of the eye in a state of such perfection, that, when used as single microscopes, they give a very perfect image of minute objects. In such lenses, which have an increasing density towards their centre, the spherical aberration is almost wholly corrected. Great care, however, must be taken to make the axis of the lens the axis of vision, to prevent its form from being injured by pressure against the aperture which holds it. The best way is to make a ring at the end of a piece of wire, having its diameter a little greater than that of the lens. A ring of viscid fluid is then made to line the ring of wire, and the lens is suspended in the ring of fluid, some of the fluid encroaching upon its anterior or posterior surface.

Magnifying Power of Single Microscopes.

Having thus described the various kinds of single microscopes, we shall now consider the subject of their magnifying power. When an eye in the prime of life, and neither long nor short sighted, views the minutest object which it can recognise, it will generally place it at the distance of about five inches. When the same object is viewed through a single microscope, the distance at which

it is seen is equal to the focal length of the lens; and as the apparent magnitude of objects is inversely as the distances at which they are seen, we have only to divide the distance, five inches, by the focal length of the lens, in order to know its magnifying power, or its apparent magnitude when seen through the lens.

The following table shows the magnifying power of lenses of all focal lengths, from 5 inches up to the 100th of an inch, and is applicable to all lenses, of whatever substance they are made.

Focal Length.	Magnifying Power.	Focal Length.	Magnifying Power.
Inches.		Inches.	
5	1	$\frac{1}{16}$	80
2	$2\frac{1}{2}$	$\frac{1}{17}$	85
$1\frac{3}{4}$	$2\frac{6}{7}$	$\frac{1}{18}$	90
$1\frac{1}{2}$	$3\frac{1}{3}$	$\frac{1}{19}$	95
$1\frac{1}{4}$	4	$\frac{1}{20}$	100
1	5	$\frac{1}{25}$	125
$\frac{3}{4}$	$6\frac{2}{3}$	$\frac{1}{30}$	150
$\frac{1}{2}$	10	$\frac{1}{35}$	175
$\frac{1}{3}$	15	$\frac{1}{40}$	200
$\frac{1}{4}$	20	$\frac{1}{45}$	225
$\frac{1}{5}$	25	$\frac{1}{50}$	250
$\frac{1}{6}$	30	$\frac{1}{55}$	275
$\frac{1}{7}$	35	$\frac{1}{60}$	300
$\frac{1}{8}$	40	$\frac{1}{65}$	325
$\frac{1}{9}$	45	$\frac{1}{70}$	350
$\frac{1}{10}$	50	$\frac{1}{75}$	375
$\frac{1}{11}$	55	$\frac{1}{80}$	400
$\frac{1}{12}$	60	$\frac{1}{85}$	425
$\frac{1}{13}$	65	$\frac{1}{90}$	450
$\frac{1}{14}$	70	$\frac{1}{95}$	475
$\frac{1}{15}$	75	$\frac{1}{100}$	500

We have already mentioned the advantages which the precious stones have over glass ones, in having a much less spherical aberration. In order that a glass lens may have the least spherical aberration, its radii of curvature must be as one to six, the flattest side being turned to the object; but this is not the case with bodies of a different refractive power. Mr Coddington, in his valuable Treatise on the Reflection and Refraction of Light,[1] has computed the ratio of the curves when the aberration is a minimum for various indices of refraction from 1·5 up to 2·0, and the amount of the aberration itself in parts of the thickness of the lens. This table is very important in a practical point of view, as will be seen from the observations which follow it.

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[1] Page 111, Cambridge, 1829.

Table showing the Spherical Aberration of Lenses of Glass and the Precious Stones, and the proper proportion of their Radii when the Aberration is a Minimum.

Substances.	Index of Refraction.	Ratio of the Radii of a Lens of Minimum Aberration.	Longitudinal Aberration, the thickness being 10.
Fluor spar; Cryolite	1·4	1 to 3·66	10·96
Glass plate; Oil of almonds; Castor oil; Honey	1·5	1 to 6	10·71
Flint glass; Quartz; Topaz; Oil of cassia	1·6	1 to 14	9·33
Glass, lead 1, flint 2; Sulphuret of carbon	1·7	1 to — 93	6·66
Sapphire; Ruby; Spinelle ruby; Garnet; Glass, lead 2, flint 1½	1·8	1 to — 12	3·57
Sulphate of lead; Glass, lead 2½, flint 1	1·9	1 to — 7	1·66
Zircon; Calomel; Sulphur; Phosphorus; Glass, lead 3, flint 1	2·0	1 to — 5	0·62

It appears from the preceding table, that when the refractive index is between 1·4 and 1·6 and a little more, but less than 1·7, the second surface of the double convex

lens must be *convex*, in order to have the least spherical aberration; but that when the index is above 1·6 or a little more, the second surface must be *concave*, in order to make the aberration a minimum, and this concavity, in the case of zircon and sulphur, is so much as — 5, so that in diamond it must be nearly — 3; so that we must sacrifice a great deal of magnifying power in order to obtain this advantage in diamond; but the sacrifice will be well bestowed, for such a lens will be almost wholly free of spherical aberration. It appears from the table, that when the index of refraction is a little less than 1·7, a plano-convex lens, with its plane side turned to the object, is the best form for a single microscope.

Notwithstanding the difficulty of the task, we would earnestly direct the attention of artists to the subject of grinding plano-convex lenses of a hyperbolic form for single microscopes. The smallness of a lens must increase the difficulty; but in this case the effect may be accidentally obtained, as it is often done in giving a parabolic and an elliptical form to specula. Mr Potter has given, and put to the test of experiment, a method of obtaining any curve derived from revolution, by giving a particular form to the grinding and polishing tools.[1]

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[1] Edinburgh Journal of Science, new series, No. 12.

CHAPTER II.

DESCRIPTION OF MICROSCOPIC DOUBLETS AND TRIPLETS.

Under this chapter we propose to describe all combinations of lenses in which two or more are placed in contact, or at such a distance that no image is formed between them.

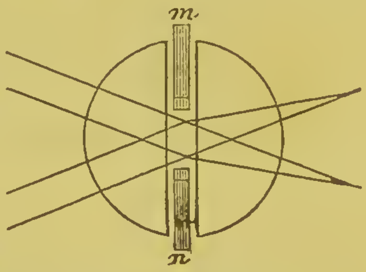
Wollaston's Periscopic Doublet.

The earliest proposal of a doublet lens was that which Dr Wollaston described in 1812,[1] under the name of a periscopic microscope. The following is his own description of it: "The great desideratum," says he, "in employing high magnifiers, is sufficiency of light; and it is accordingly expedient to make the aperture of the little lens as large as is consistent with distinct vision. But if the object to be viewed is of such magnitude as to appear under an angle

[1] Phil. Trans. 1812, p. 375

of several degrees on each side of the centre, the requisite distinctness cannot be given to the whole surface by a common lens, in consequence of the confusion occasioned by oblique incidence of the lateral rays, excepting by means of a very small aperture, and proportionable diminution of light. In order to remedy this inconvenience, I conceived that the perforated metal which limits the aperture of the lens might be placed with advantage in its centre; and accordingly I procured two plano-convex lenses ground to the same radius, and applying their plane surface on opposite sides of the same aperture, in a thin piece of metal (as is represented by a section, fig. 7), I produced the desired effect, having virtually a double convex lens, so contrived that the passage of oblique pencils was at right angles with its surface, as well as the central pencil. With a lens so constructed, the perforation that appeared to give the most perfect distinctness was about *one-fifth* part of the focal length in diameter; and when such an aperture is well centred, the visible field is at least as much as 20° in diameter. It is true, that a portion of light is lost by doubling the number of surfaces; but this is more than compensated by the greater aperture which, under these circumstances, is compatible with distinct vision."

Fig. 7.



Periscopic Sphere.

In the preceding passage Dr Wollaston describes only a double convex periscopic microscope, consisting of two plano-convex lenses; but he does not take the case where these two lenses are hemispheres, and, consequently, where the doubly convex one which they form is a sphere. When the lenses are not hemispheres, the pencils are not centrical, and the rays from different parts of the object do not each suffer the same species of refraction as they do when passing through a sphere, so that every part of the field is not equally distinct. It is obvious also that Dr Wollaston did not think of filling up the central aperture with a fluid of the same refractive power as the lens, in order to remove the loss of light from the double number of surfaces, which he mentions as a defect in his microscope.

The construction of a periscopic sphere proposed by Sir David Brewster combines these two properties. The lenses, whether they are hemispherical or not, must be so placed that their convex surfaces form part of the same sphere, as shown in the annexed figures.

Fig. 8.

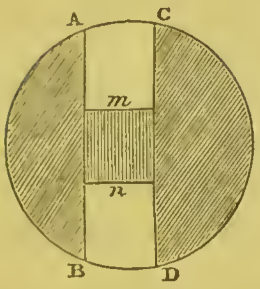


Fig. 9.

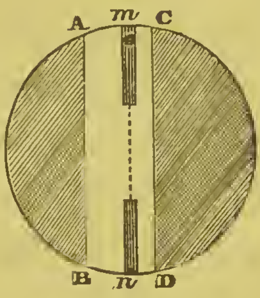


Fig. 10.

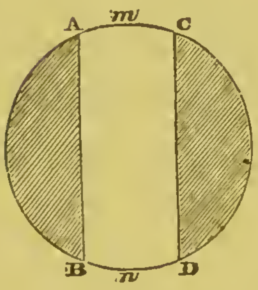
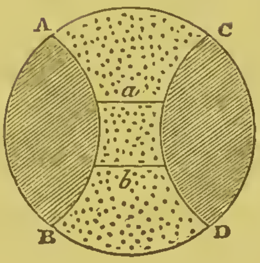


Fig. 11.



In fig. 8, the plano-convex lenses AB, CD may be cemented to a piece of plate-glass *mn*, of such a thickness in one direction as to complete the sphere, and of such a diameter in the direction *mn* as to form a suitable contraction of the aperture.

In fig. 9, the space between the lenses may be filled up, as in the figure, by two pieces of plate-glass A*mn*B, C*mn*D, between which is a plate of brass, or of thin black paper, containing a suitable aperture in the centre of the lenses. Here there are *six* surfaces within the sphere, but, by uniting them with a proper cement, the whole becomes a single sphere, in which there is no perceptible loss of light.

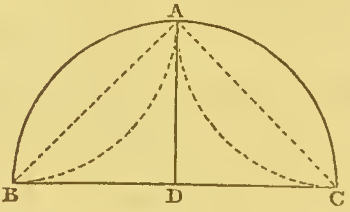
In fig. 10, lenses of unequal size and thickness are com-

bined, either with a plate of glass, or a fluid between them of the same refractive power as the glass, and the apertures may be placed on the plane surfaces AB, CD.

In fig. 11, two convex lenses may be combined into a sphere, the intermediate portion being filled up with a fluid of the same refractive power. This may be readily done by cementing each lens on the end of a brass or glass tube *ab*, and introducing the fluid by an aperture.

In uniting these lenses, it is obviously necessary that the convex outer surfaces should be exactly of the same curvature, and of the same kind of glass. The best way of effecting this is to grind a thick lens ABC, either greater or less than a hemisphere, and then to bisect it at AD, and out of the portions ADB, ADC to form two plano-convex or two double convex lenses AB, CD. The outer surfaces of these two lenses will belong accurately to the same sphere. The perfect similarity of the inner surfaces is of less consequence, as all refraction by them is removed by the cement.

Fig. 12.

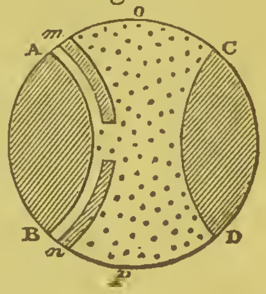


By these different steps Sir David Brewster was led to the idea of the grooved sphere, or the lens already described under the head of single microscopes, in which the aperture is contracted by excavating the sphere all round in one of its great circles.

Periscopic Achromatic Spheres.

If, in the construction shown in fig. 13, in place of making the fluid *op* of the same refractive and dispersive power as the two lenses, we make it such as to correct the colour of these lenses, we shall obtain an achromatic sphere, as proposed by Sir David Brewster; and the compound lens may be still farther improved as a microscope, by attaching, either by cement or not, to the back of the first lens AB a convex speculum of silver or steel for illuminating the object, the contracted aperture being the hole in the centre of the speculum. The concave fluid lens is shown at *op*; and such a curvature must be given to the convex reflector *mn*, that it may reflect parallel or diverging rays upon the object.[1]

Fig. 13.



Mr Coddington,[2] in his excellent treatise on optics, thus treats of the preceding contrivance.

"An achromatic sphere may be constructed by interpos-

[1] Edinburgh Philosophical Journal, vol. iii.; and Mr Pritchard's Treatise on Optical Instruments, in the Library of Useful Knowledge, p. 41, § 66.

[2] Treatise on the Reflection and Refraction of Light, p. 256.

ing between two crossed lenses (double convex ones), in opposite positions, a concave lens of a medium more highly dispersive than that of the lenses, adjusting the curvatures so that the outer surfaces of the crossed lenses shall be portions of the same sphere, and that the interior surfaces shall exactly fit into each other.

"In such a system, we may consider the effect to be the same as that of an entire sphere of the same medium as the two lenses diminished by that of a concave lens having for its refractive ratio that which exists between the two media in question.

"Thus, if μ_1 be the ordinary index of refraction for the convex lenses, μ_2 for the concave one, $\pi : 1$ the ratio of the dispersive powers, r the radius of the sphere, s, σ those of the internal surfaces, we must have

$$\left(\frac{\mu_2}{\mu_1} - 1\right)\left(\frac{1}{s} + \frac{1}{\sigma}\right) : 2\,\frac{\mu_1 - 1}{\mu_1}\;\frac{1}{r} = \pi : 1;$$

whence it follows, that $\frac{1}{s} + \frac{1}{\sigma} = 2\,\pi.\,\frac{\mu_1 - 1}{\mu_2 - \mu_1}\;\frac{1}{r}.$

For example, let $\mu_1 = 1{,}5$; $\mu_2 = 1{,}65$; $\pi = {}_1 1{,}25$.

Then, $\frac{1}{s} + \frac{1}{\sigma} = \frac{1}{4}\cdot\frac{,5}{{}_1,5}\;\frac{1}{r} = \frac{1}{1,\,2r}$

If the first internal surface be plane, or $s = \infty$, we have in general $\sigma = \frac{1}{2\,\pi}\,\frac{\mu_2 - \mu_1}{\mu_1 - 1}\,r$; or, in this particular example, $\sigma = 1{,}2r$, or $\sigma : r = 6 : 5$."

Doublet of no Aberration.

So long ago as 1668, a doublet was described in the Philosophical Transactions, in which a large and flat field was obtained. This subject, however, was never investigated with care till Sir John Herschel took up the subject in 1821. The doublet, made of glass, which Sir John proposes for obtaining perfect distinctness in microscopical observations is shown in the annexed figures, 14, 15, the convex sides being turned to the eye when the doublet is used as a microscope, and to the sun when it is used as a burning-glass.

Fig. 14.

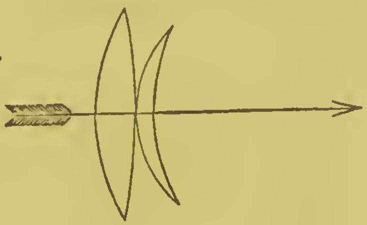
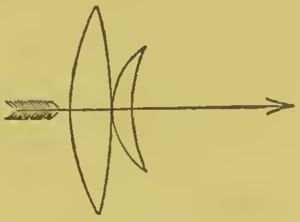


Fig. 15.



The following are the radii and focal length of these lenses.

	Fig. 14.	Fig. 15.
Focal length of the *first* lens........	+ 10·000	+ 10·000
Radius of its first surface...........	+ 5·833	+ 5·833
Radius of its second surface........	— 35·000	— 35·000
Focal length of the *second* lens......	+ 17·829	+ 5·497
Radius of its first surface...........	+ 3·688	+ 2·954
Radius of its second surface........	+ 6·291	+ 8·128
Focal length of the *combined* lenses	+ 6·407	+ 3·474

"Whether we ought or ought not," says Sir John, "to aim at the rigorous destruction of rays parallel to the axis, the use to which the lens is to be applied must decide. In a burning-glass it is of the highest importance. A slight consideration will suffice to show, that the difference of temperatures produced in the foci of a double convex lens of equal radii, and one of the same focal length, but of the best form, must be very considerable. In order to try whether even the latter might not be improved by the shortening of the focus, and the superior concentration of the exterior rays, by applying a correcting lens of one of the forms above calculated, in spite of the loss of heat in passing through a second glass, I procured two lenses to be figured to the radii assigned in the first column of the foregoing table. They were about three inches in aperture, and when combined as above described, the aberration was almost totally destroyed, and probably would have been so completely had the index of refraction proper to the glass been employed instead of that adopted in our calculation for brevity. Their combined effect as a burning-lens appeared to me decidedly superior to that of the first lens used alone, and there is therefore good reason to presume, that the effect of the other construction, which, with the same loss of heat, affords a much greater contraction of the focus, would be still better; and I regret not having tried it in preference.

"In eye-glasses and magnifiers, if we would examine a minute object with much attention, as a small insect, or (when applied to astronomical purposes) if we would scrutinize the appearance of a planet, a lunar mountain, the nucleus of a comet, or a close double star, where extent of field is of less consequence than perfect distinctness in the central point, too much pains cannot be taken in destroying the central aberration."[1]

Mr Pritchard informs us, that he has executed some of these doublets for the object-glasses of compound microscopes, "for which," he says, "they answer remarkably well, but their angle of aperture is small compared with combinations of double achromatics."[2]

Herschel's Periscopic Doublet.

We owe also to Sir John Herschel the construction of a periscopic doublet with a very large field of moderate distinctness. "In spectacles," says he, "reading-glasses, magnifiers of moderate power, and eye glasses for certain astronomical purposes, the correction of the aberration in the centre of the field may be sacrificed with little inconvenience. By far the best periscopic combination I am

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[1] Phil. Trans. 1821, p. 246–248.

[2] Microscopic Cabinet, p. 163.

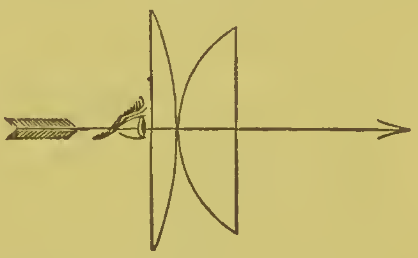
acquainted with consists of a double convex lens of the best form, but placed in its worst position (radii as 6 to 1) for the lens next the eye, and a plane concave whose focal length is to that of the other as 2·6 to 1, or as 13 to 5, placed in contact with its flatter surface, and having its concavity towards the object, as in the annexed figure, for the farthest; yet for destroying the aberration of rays parallel to the axis nothing can be worse. In fact our formula gives for the aberration in this construction 22·02, or about 22 times what the best single lens of equal power would give; yet, on accidentally combining two such lenses in this manner, I was immediately struck with the remarkable extent of oblique vision, with the absence of fatigue on reading some lines with a power much beyond that of the natural eye, and with the freedom from colour at the edges of the field, arising from *the opposition of the prismatic refractions* of the two solids, an advantage which a single meniscus does not possess." The focal length of the compound lens which Sir John tried was 1·84 of an inch. The field of tolerably distinct vision extended fully 40° from the axis, and the letters of a book might be read, and the forms of objects distinguished, with management, as far as the 75th degree. In using such a combination the lenses should be very thin, and the eye applied as close as possible.

Fig. 16.

Plano-Convex Doublet.

A doublet of much simpler construction, and with its spherical aberration greatly diminished, has also been proposed by Sir John Herschel. It is represented in the annexed figure, and consists of two convex lenses of equal focal lengths, the convex sides being placed in contact, and the eye and object opposite the plane sides. In this case the aberration will be only 0·6028. But if we make the focal length of the first to that of the second as 1 to 2·3, the aberration will be reduced to 0·2481. In order to have an idea of the value of such a doublet, we shall give the series of aberrations for single lenses, as investigated by Sir John Herschel.

Fig. 17.



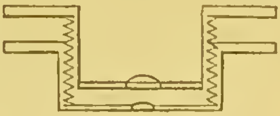
	Aberration.
Plano-convex, plane side first	4·2
Plano-convex, convex side first	10·81
Double convex	1·567
Best form of a single lens	1·00
Doublet of two equal plano-convex lenses	0·6028
Doublet of two plano-convex lenses with their focal lengths as 1 to 2·3	0·2481
Doublet of garnet, with suitable focal lengths	0·08

As these calculations are made for glass, the advantage of such a doublet made of garnet or sapphire must be much greater. In a garnet the minimum aberration takes place when the form of the lens differs very little from that of plano-convex; and as it is then to that of glass as 35 to 107, the aberration will be only about 0·08, or next to imperceptible.

Wollaston's Doublet.

The consideration of the Huygenian eye-piece for astronomical telescopes suggested to Dr Wollaston the probability that a similar combination should have a similar advantage, of correcting both achromatic and spherical aberrations, if employed in an opposite direction as a microscope.[1] With this view, he took two plano-convex lenses, the ratio of whose focal lengths was as 3 to 1, and he placed them as in the annexed figure, so that the distance of their plain surfaces was from $1\frac{4}{10}$ to $1\frac{5}{10}$ of the focal length of the smallest. The plane sides of the lenses are towards the object. The advantage of the first lens having its

Fig. 18.



[1] Mr Coddington has shown that such a correction is impossible. (*Treatise on the Eye and Optical Instruments*, p. 55.)

plane side next the object is, as Dr Wollaston states, that if it should touch a fluid, the view is not only not impaired, but improved, whereas a double convex lens would require to be taken out and cleaned. The following excellent observations on this doublet are made by Pritchard.

"Having mounted some plano-convex lenses of the relative foci named by Dr Wollaston, in such a manner that the distances might be varied at pleasure, I was surprised to find, that after the doublet was adjusted *by trial,* so as to obtain the maximum of distinctness, the distance between the lenses did not accord either with the rule given by Huygens, or that of Dr Wollaston. Supposing that I had not got the combination intended by Dr Wollaston, I procured several doublets made by different artists, and to my astonishment found they agreed with my own, and therefore presumed the doctor was mistaken in the distance by the thickness of the lenses and the minuteness of the space between them. The distance which appeared to me essential to obtain the best effect, *is the difference of the focal length of the two lenses, making a proper allowance for their thickness.* The proportion of the foci of the two lenses may be varied *ad libitum.* All that is requisite in this respect is, that the difference must be greater than the thickness of the anterior lens, while it may be observed (in high powers), that the greater the difference between their two focal lengths, the more space will be left in front; and as

this is of great practical importance, they should never be less than as 1 to 3. I have made some very good ones, differing as much as 1 to 6. Another advantage resulting from attending to this point is, that we do not lose so much magnifying power in such combinations as when the difference between the lenses is less.

"The delicacy and beauty with which these doublets exhibit the structure of tissues will justify my entering into some minute details respecting them. The following is necessary to insure their goodness.

"*First*, The convex surface of each lens must be *truly spherical*. If this is not obtained, it will be in vain to procure a good doublet, however beautifully the lenses may be polished, or accurately adjusted. From this circumstance, I have found globules perform very well, providing they are free from air-bubbles, which, however, is rarely the case. It should be observed, that a slight scratch on their surface is trifling compared to air-bubbles; for the latter not only stop the light, but, by the reflection around the edges of each bubble, produce considerable fog or glare. *Second*, The distance between the lenses is the next point of importance; its adjustment is best accomplished by trial, mounting the lenses in such a manner that their distance can be varied at pleasure, and capable of being turned round, so as to adjust the centring. When this is obtained, they should be fixed so that their distance and

position cannot be altered. This it is necessary to regard, as I have sometimes spent whole days in re-adjusting a doublet that had been separated to examine the lenses singly. *Third*, The stop or diaphragm, for limiting the aperture in these combinations, should be placed immediately behind the anterior lens. From the difference of the situation of this stop in the various doublets I have examined, it will appear that their makers did not know that the field of view depended upon the plane of the stop. I have found, that when the stop is situated *close* behind the anterior lens, no other is required, and the field is enlarged without sensibly augmenting the aberration. On this account, the lenses of the finest doublet, when used singly with the same aperture as combined, has so much aberration and distortion that distinct vision cannot be obtained, even with the most rigid adjustment of the focus. From the difficulty of procuring a flat surface, some makers have worked the anterior surface of the lens next the object concave: these lenses do not possess any advantage in point of performance, not even to compensate for the loss of power from the negative side."

Mr Pritchard remarks, that when the lens next the object is a jewel, the performance of the doublet is improved; but that he has not observed any advantage when both lenses are gems. This must be a mistake; for lenses of any gem, that are superior to glass ones when acting singly,

must, if suitably combined, be superior also when united. In proof of this, we have a garnet doublet before us, executed by Mr Blackie, the performance of which is quite remarkable. The lenses are made of Elie garnets, and their convex sides are placed towards each other. The radius of the smallest lens near the object is $\frac{1}{70}$th (*one seventieth*) of an inch, and that of the other $\frac{1}{20}$th (*one twentieth*) of an inch. Its magnifying power is very high, exceeding greatly that of the semi-jewel doublet made by Mr Pritchard, with a sapphire lens $\frac{1}{60}$th (*one sixtieth*) of an inch focus, combined with a glass lens $\frac{1}{10}$th (*one tenth*) of an inch focus.

In the experiments to which we have already referred on fluid lenses, Sir David Brewster has constructed doublets, one of the lenses of which is made of glass or a precious stone, and the other a fluid one; and he has been enabled to increase the power of any single lens by the addition of a fluid one, till the object touches the anterior surface of the object-lens. He has also made fluid spheres contracted in the middle, and fluid doublets in which the centring is effected by an infallible process.

Pritchard's Triplet.

Upon the same principle as the doublets, Mr Pritchard has constructed triplets, the third or posterior lens having a longer focal length than the two others. This combina-

tion requires much more precision in the adjustment, and more attention in the centring. Mr Pritchard remarks, that, "when perfected, they amply repay the pains bestowed upon them, in the accuracy with which they exhibit the most difficult lined objects, though it is to be regretted that neither these nor the doublets of deep power will show pleasantly cylindrical bodies of large diameter, such as a large mouse or bat's hair." Having long made use of one of Mr Pritchard's triplets, we can amply confirm the account which he has given of the excellence of this combination. Mr Blackie has executed for us a triplet, the centre lens of which is garnet, the posterior one of quartz, and the anterior one of flat glass. It is a very powerful combination, and performs admirably.

Sir David Brewster has made triplets in which two of the lenses are fluids and the third a solid, and some in which they are all fluids.

Single Achromatic Microscope.

In many of the doublets which we have already described, the chromatic aberration is partially, and sometimes greatly corrected, but still not to such a degree as to entitle them to the name of achromatic. The great improvement which has taken place in the art of grinding and polishing small lenses, has enabled the optician to execute

double and *triple* achromatic lenses, having a diameter so small as from $\frac{1}{4}$th to $\frac{1}{16}$th of an inch. Mr Pritchard has made them of the latter size with an angle of aperture of 65°. These lenses may be advantageously used where very high powers are not required, or when they cannot be applied, though it is usual to employ them as the object-glasses of compound microscopes, as we shall afterwards see.

Sir David Brewster has executed achromatic lenses, both *double* and *triple*, by combining a fluid *concave* lens with one or two convex lenses of the precious stones or glass. When the lenses are *double*, the fluid lens is of course a meniscus in which the concavity predominates, as it is impossible to form a fluid lens doubly concave.

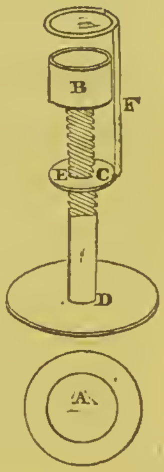
Single Reflecting Microscopes.

Single reflecting microscopes are not much in use. They consist of a concave metallic speculum of a short focal length, so that any minute body placed in its focus will be seen magnified. The form of the speculum should of course be parabolic. Such a microscope is principally useful for looking at one's own eye, or any part of it not far from the pupil. In these cases no image is formed, as the rays enter the eye parallel.

The following ingenious contrivance for a fluid reflect-

ing microscope we owe to Mr Stephen Gray.[1] Having taken a small globule of quicksilver, and dissolved it in a menstruum of 10 parts of water and 1 of nitric acid (aquafortis), he dipped the end of a stick in this solution, and rubbed with it the inner circle of the ring A, so as to give it a mercurial tincture. This ring is made of brass, and is about the 30th of an inch thick, having its mean diameter not exceeding $\frac{2}{5}$ths of an inch. When the inner surface of the ring wetted with the solution has been wiped dry and laid upon a table, pour a drop of quicksilver within it, and when this drop is gently pressed with the ball of the finger, it will adhere to the ring, and when cleansed with a hare's foot will form a *convex* speculum. If the ring and speculum are now taken up and carried horizontally, and laid on the margin of the hollow cylinder B, the mercury will become a *concave* reflecting speculum, in consequence of its upper surface sinking down by gravity. The cylinder B rests upon a pillar with a screw on its outside, and supported by the base D. A stage, ECFG, may be moved up and down, so as to place the object, which is fixed at G, in the focus of the concave speculum.

Fig. 19.



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[1] Phil. Trans. 1697, No. 228, p. 539.

CHAPTER III.

ON COMPOUND MICROSCOPES.

A compound microscope is an instrument in which a distinct and enlarged image of an object is formed by an object-glass or a speculum, and this enlarged image again magnified by one or more eye-glasses.

There is every reason to believe, that the earliest compound microscopes, which were used by Zansz and Galileo, consisted of a convex lens for an object-glass, and a concave one for an eye-glass, like the telescope which was at that time in use.

Fontana in 1646 used *two* convex lenses; Dr Hooke *three*, and Eustachio Divini *four*; the two next the eye being plano-convex, and placed in contact, with their convex sides towards each other, to give a high power and a large and flat field. In 1691 Philip Bonnani[1] used a com-

[1] *Observationes circa viventia, quæ in rebus non viventibus reperiuntur.*

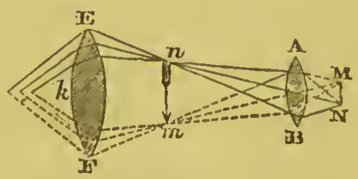
pound microscope with three lenses, and added to it an illuminating apparatus with two lenses.

The reflecting compound microscope was first suggested by Sir Isaac Newton, and its construction varied and made more complex by Dr Barker and Dr Smith of Cambridge. The simple contrivance of Sir Isaac has in modern times been greatly improved by Amici, Potter, Tulley, Cuthbert, and Dr Goring, whose labours in improving the microscope have been indefatigable, and in the highest degree successful. An account of these improvements will be given in this chapter.

Compound Refracting Microscope.

The principle of the compound microscope with two lenses will be understood from the annexed figure, where MN is a minute object placed in the focus of the object-glass AB, or rather a little farther from it than its principal focus. An image of this object will be formed at *mn*, at some distance behind AB, the distance *n*A increasing as AM diminishes. The size of the image *mn* will be to that of the object MN as *n*A is to AM, their distances from the lens AB. If we now view this magnified image *mn* through an eye-glass EF, so

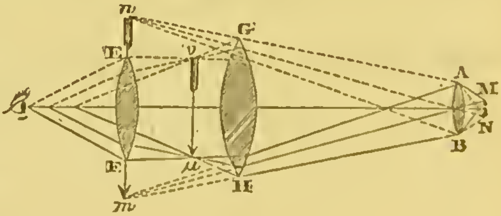
Fig. 20.



placed that *mn* is in its principal focus, we shall again magnify it in the inverse proportion of E*n* to the distance at which the eye sees minute objects most distinctly, which is about five inches. The object MN is thus doubly magnified, so that if *n*A is six times AM, and the lens EF has a focal length of half an inch, the magnifying power will be $6 \times \overline{5 \div \frac{1}{2}} = 60$. While the lenses are the same, the magnifying power may be increased to any extent by increasing the distance between the lenses EF and AB; but the object becomes indistinct as the magnifying power increases, so that it is not advisable to make the distance *n*A more than five, six, or seven inches; or calling f the focal distance of the eye-glass, $D = AM$, $d = An$, and Δ the distance at which we see objects distinctly, then this magnifying power M will be $M = \frac{d}{D} \times \frac{\Delta}{f}$.

In this arrangement of lenses the field of view is small, and therefore we cannot see the whole of many objects at one view. In order to remedy this, a large lens, called the amplifying glass, is placed between the image and the object-glass, as shown in fig. 21, where *nm* is the image formed by AB alone; but in con-

Fig. 21.



sequence of the interposition of GH, it is contracted into $\nu\mu$, and this contracted image is magnified by the eye-glass EF. In order to widen the field still farther, and make it flat, two plano-convex lenses have been placed at E, F, having their convex sides in contact. In order to find the magnifying power when the lens GH is used, we must multiply the magnifying power, as obtained by the preceding formula, by the quantity $\frac{L}{\varphi}$, φ representing the focal length of the lens GH and $L = \frac{\delta^2}{\delta - \varphi} - d' - f$, δ being the distance between the first and second glasses, and d the distance between the first and third glasses.

Dr Goring prefers the following method of finding the magnifying power of these microscopes. Measure the aperture of the object-glass and call it a, make $AM = f$, and having measured with a micrometer scale the diameter of the usual pencil of rays before they enter the eye, call it d; then $a : f = d :$ F, F being the focal length of a single lens having the same power as the compound microscope. But the magnifying power m of a lens F is $\frac{\Delta}{F}$. Hence the magnifying power M of the compound microscope will be $M = \frac{\Delta a}{fa}$.

In accurate investigations with the microscope, the common compound refracting instrument above described is of

little use, and has been superseded by better combinations. As it is, however, very serviceable for common purposes, we shall describe one of them of the most convenient and modern construction. This instrument is shown in Plate IV. fig. 19, where the body of the microscope and all its parts are seen. They all slide on a triangular bar S, the sliding pieces having springs on one side. The three lenses within the body of the microscope are shown at EF, GH, AB, as in the last figure. The object MN is placed on a slider attached to the stage PQ. The reflector for illuminating the field is at R, being moved by a Hooke's universal joint at XX. A condensing lens is placed at C, for increasing the light reflected from the mirror R. The body of the instrument is adjusted to distinct vision of the object MN, by a rack and pinion working a triangular bar at right angles to the bar S. It is often thought preferable to move the stage towards the microscope, rather than the microscope towards the stage; but as the motion of the stage often disturbs animalculæ, and may derange the position of inanimate objects, the motion of the body of the microscope has many advantages. When the stage, however, is moveable, it is made to consist of *three* plates. The upper plate, which carries the slider-holder, is secured with a screw across the middle plate, which middle plate is carried across the lower stage-plate by a similar motion, but in a direction at right angles to

the upper plate. By these movements the object can be placed in any position with regard to the axis of the fixed microscope, first by turning the one screw and then the other.

Some attention is requisite in adjusting the apertures of the object-glasses employed. The smaller they are, the less will be the spherical and chromatic aberration of the object-glass, but the less will be the light. When a plano-convex lens about half an inch focus is used, its plane side should be towards the object, and its aperture limited to $\frac{1}{15}$th of an inch.

A compound microscope is sometimes so constructed that it can be used as a single microscope. This is done by screwing the lower end of the body round the object-glass into a projecting arm at the top of the stand. When the body is unscrewed and removed, a single lens or a doublet or triplet may be screwed into the same place, and the moveable stage, with the slider and object, brought near the single lens, just as if it had been the object-glass of a compound microscope.

Dr Goring's Improvement on the Object-Glass of the Compound Microscope.

When the compound microscope does not require to have a high power, a compound object-glass of two lenses may be advantageously employed. Dr Goring[1] has contrived the combination

Fig. 22.

shown in the annexed figure, where A is a plano-convex lens, with its flat side next the object, having its focal distance about one half or two thirds that of the plano or double convex lens B. A stop D is placed in the posterior focus of the object-glass A. Mr Pritchard remarks, that when the focal length of A "is not less than half an inch, this combination has been employed with considerable advantage, both as regards distinctness and aperture."

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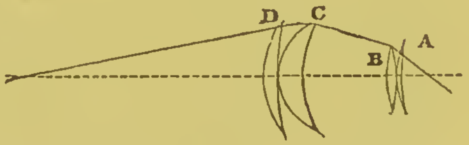
[1] Quarterly Journal, vol. xvii. p. 202.

Mr Coddington's Improvement on the Eye-Glasses of the Compound Microscope.

The improvement suggested by Mr Coddington on the eye-pieces of compound microscopes is shown in Plate IV. fig. 20. The object of the contrivance is to fulfil the condition proposed by Huygens in his excellent telescopic eye-piece, namely, to have the refraction of the pencils divided between the two lenses, and to produce the greatest possible flattening of the field. Mr Coddington found that the most proper form of the lenses was that shown in the annexed figure, where the two eye-glasses consist of a meniscus A next the eye, and a double equi-convex lens B, while the field-glass is composed of two meniscuses C, D.

Fig. 23.



Mr Coddington, however, informs us, that he "found no sensible error arise from the substitution of plano-convex lenses for the meniscus-glasses, which are difficult and expensive to form." He remarks also, that theory indicates "a farther flattening of the field to be made by separating the eye-glasses a little, which requires the distance of the first eye-glass from the field-glass to be diminished by about half as much;" but he did not perceive any improvement arising from

this alteration in practice, and therefore he does not recommend the change. The object-glass which Mr Coddington uses in this microscope is shown at *o*, and is the grooved sphere proposed by Sir David Brewster.

In his treatise on the eye and optical instruments, Mr Coddington has proposed a different combination for the eye-glasses and the field or amplifying-glass. Supposing the distance between the object-glass and field-glass to be 1 inch, and the focal length of the field and eye-glasses 1 inch each, and the distance between the field-glass and nearest eye-glass 1 inch, he finds the distance of the two eye-glasses to be $\frac{1}{5}$th of an inch. He finds also, "that all indistinctness arising from the oblique refractions will be corrected when the field-glass is convexo-convex, nearly convexo-plane, the first eye-glass convexo-convex[1] (radii as 3 : 1), and the second eye-glass a meniscus[2] (radii as 1 : 5)."

Taking another case, he supposes the distance of the object-glass from the field-glass to be 2 inches, and the eye-glasses to be in contact, as in fig. 23, then "it appears that for the achromatism we must have the distance between the field-glass and second eye-glass 1 inch." Then the field-glass must be convexo-plane nearly; the

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[1] The flattest side next the eye.

[2] The most convex side next the eye.

first eye-glass equi-convex, and the second eye-glass a meniscus with the radii as 1 : 5.

Dr Goring, who examined one of the instruments constructed on these principles, states, *that both the chromatic and spherical aberration of the objective part was wholly untouched, and that the eye-piece, consisting of four glasses, was achromatic.* He adds also, that nothing can surpass the beauty of the field of this microscope for extent of flatness. Now we think that Dr Goring has mistaken Mr Coddington, who never pretended to correct the spherical and chromatic aberration of the object-glass.[1] He considers the chromatic and spherical aberration of the grooved sphere, which is the object-glass he uses, as reduced to very small quantities, by leaving only a small channel in its axis for the passage of the rays. Whatever the residual aberration may be, Mr Coddington is not answerable for it, as his object was merely to make the other part of the microscope good, which, according to Dr Goring, he has succeeded in doing.

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[1] Treatise on the Eye and Optical Instruments, p. 58, 59, § 329.

Compound Achromatic Microscope.

Although the achromatic microscope has only recently come into use as an effective and superior instrument, yet it can scarcely be considered as a new instrument. Every person knew that an achromatic object-glass was most desirable in a compound microscope. So early as 1776 Euler proposed to employ them in compound microscopes; but so late as 1821 M. Biot considered their introduction as out of the question, from the impracticability of achromatizing lenses as small as those which the microscope requires.

In 1823 M. Selligues and Dr Goring were both occupied with the subject, the former having employed MM. Chevalier, two excellent opticians in Paris, and the latter Mr Tulley, to execute small achromatic object-glasses. It is to M. Selligues, however, in so far as we can learn, that we are indebted for the new and happy idea of making the object-glass consist of *four* achromatic compound lenses, each consisting of two lenses. This idea is the actual source of the superiority of the achromatic microscopes; and in proof of this we may state, that Professor Amici, who had early been following out the old idea of a single achromatic object-glass, abandoned his attempts in 1815, but afterwards successfully resumed them by adopting M. Selligues' plan of the superposition

of several object-glasses. In M. Selligues' instrument the focal length of each object-glass was 18 lines, its diameter 6 lines, and its thickness at the centre 6 lines. In that of Amici the focal length of each was about 6 lines; and MM. Chevalier have executed them having only 2 lines in focal length. More recently, however, Mr Pritchard has surpassed all these artists, by making them of one sixteenth of an inch in focal length.

From this brief historical detail, we shall proceed to give a more minute account of the lenses executed by these different individuals, for which we are indebted to Mr Jackson Lister, whose able memoir on this subject is, as we shall see, one of the most valuable contributions to the science of the microscope that has for a long time appeared.

The achromatic object-glasses of M. Selligues' microscope made by MM. Chevalier, consisted of a plano-concave lens of flint glass, and a double convex one of crown or plate glass, with their inner curves cemented together by a mixture of mastic and turpentine, to remove the reflection of the interior surfaces, and prevent the introduction of dampness. Four of these lenses, of from $1\frac{1}{2}$ to $1\frac{7}{8}$ of an inch in focal length, were made to screw before each other, so as to be used either all together, or any of them individually, in the usual manner, like the object-glasses of a compound microscope. The aberration of colour was thus

corrected in a considerable degree, but the glasses were fixed in their places, with their convex sides towards the object, which is their worst position; and in consequence of this, the spherical aberration was enormous, and was distinctly seen, even with the small aperture to which it was necessary to reduce them.

Notwithstanding this defect, the grand idea of the combination was acquired; and M. Chevalier having observed the mistake committed by M. Selligues, made them of less focal length, and more achromatic; and turning the concave lens to the object, he produced in 1825 an instrument far above that of M. Selligues. His deepest glasses were four tenths of an inch in focal length; and in his first microscope two such compound lenses were combined for his highest power.

The date of Fraunhofer's achromatic microscopes is not known. Many years ago the writer of this article ordered an achromatic object-glass from Fraunhofer for a large microscope, for the purpose of making a particular class of observations; but at that time he seems not to have made any compound lenses to be combined after the manner of Selligues. Mr Robert Brown[1] has a series of five such object-glasses, recently obtained from Utz-

[1] Phil. Trans. 1830, p. 188.

schneider, whose focal lengths are from 1·8 to 0·43 of an inch.

When Professor Amici visited London in 1827, he brought with him some compound object-glasses, which performed very well; and Mr Lister has since learned from him, that he has executed a combination of 2·7 lines in focal length, and 2·7 lines in aperture, which greatly excels the former.

Among the most successful improvers of the achromatic microscope we must rank Mr Jackson Lister, who has discovered some curious and valuable properties of these lenses that have escaped the notice of the most skilful analysts. Mr Lister has investigated the subject entirely as a matter of observation, and therefore his results are more likely to have a higher practical value.

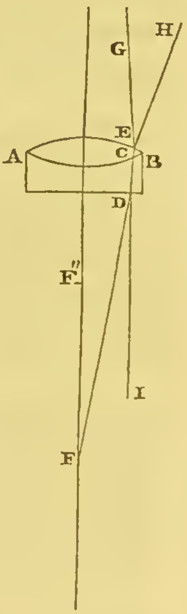
Mr Lister takes as the basis of a microscopic object-glass two conditions, 1. that the flint glass shall be plano-concave; and, 2. that it shall be joined by some cement to the convex lens. The *first* condition obviates the risk of error in centring the two curves, and the *second* diminishes by nearly a half the loss of light from reflection, which is very great at the numerous surfaces of a combination of compound object-glasses.

Now Mr Lister has found that in every such compound lens which he has tried, whether the flint glass was Swiss or English, with a double convex of plate glass, which has

been rendered achromatic by the form given to the outer curve of plate glass, the ratio between the refractive and dispersive powers has been such that its figure has been correct for rays issuing from some point in its axis not far from the principal focus on its plane side; and these rays either tend to a conjugate focus within the tube of the microscope, or emerge nearly parallel.

If AB represents such an object-glass, let us suppose that it is free from spherical and achromatic aberration for a ray FDEG radiating from F, then the angle of emergence GEH will be about three times as great as that of incidence FDI. If the radiant point is now made to approach the lens, the angles of incidence and emergence will approach to equality, and the spherical aberration produced by the two will bear a less proportion to the opposing error of the single correcting curve ABC, and hence in this case the rays will be *over-corrected* for such a focus.

Fig. 24.



As F continues to approach the lens, the angle of incidence continuing to increase, it will exceed that of emergence, which has been in the mean time diminishing, so that the spherical aberration produced by the two outer surfaces will recover their original proportion. When F has reached this point F″ (at which the

angle of incidence does not exceed that of emergence so much as it had at first come short of it), the rays will again be free from spherical aberration. If F″ still comes nearer the lens, or is carried beyond F in the opposite direction, the angle of incidence in the former case, or of emergence in the latter, becomes disproportionately effective, and in either case the aberration exceeds the correction, or the rays are *under-corrected*. Hence Mr Lister gives the following rule.

" *That in general an achromatic object-glass, of which the inner surfaces are in contact, or nearly so, will have on one side of it two foci in its axis, for the rays proceeding from which the spherical aberration will be truly corrected at a moderate aperture; that for the space between these two points, its spherical aberration will be over-corrected, and beyond them either way, under-corrected.*"

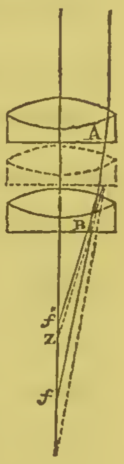
Mr Lister found also, " that when the longer aplanatic focus is used, the marginal rays of a pencil not coincident with the axis of the glass are distorted, so that a coma is thrown outwards, while the contrary effect of a coma directed towards the centre of the field is produced by the rays from the shorter focus." These interesting results obviously furnish the means of destroying both aberrations in a large focal pencil, and of thus surmounting what has been hitherto the chief obstacle to the perfection of the microscope. And when it is considered that the

curves of its diminutive object-glasses have required to be at least as exactly proportioned as those of a large telescope, to give the image of a bright point equally sharp and colourless, and that any change made to correct one aberration was liable to disturb the other, some idea may be formed of what the amount of that obstacle would have been. It will, however, be evident, that if any object-glass is but made achromatic, with its lenses truly worked and cemented, so that their axes coincide, it may with certainty be connected with another possessing the same requisites, and of suitable focus, so that the combination shall be free from spherical error also in the centre of its field.

For this the rays have only to be received by the front glass B, from its shorter aplanatic focus F, and transmitted in the direction of the larger correct pencil FA of the other glass A. It is desirable that the latter pencil should neither converge to a very short focus, nor be more than very slightly, if at all, divergent; and a little attention at first to the kind of glass used will keep it within this range, the denser flint being suited to the glasses of shorter focus and larger angle of aperture. If the two glasses which in the diagram are drawn as at some distance apart, are brought nearer together (if the place of A, for instance, is carried to the dotted figure), the rays transmitted by B in the direction of the larger aplanatic pencil of A, will

plainly be derived from some point (Z) more distant than F″, and lying between the aplanatic foci of B; therefore (according to what has been stated) this glass, and consequently the combination, will then be spherically over-corrected. If, on the other hand, the distance between A and B is increased, the opposite effects are of course produced.

Fig. 25.



In combining several glasses together, it is often convenient to transmit an under-corrected pencil from the front glass, and to counteract its error by over-correction in the middle one.

Slight errors in colour may, in the same manner, be destroyed by opposite ones; and, on the principles described, we not only acquire fine correction for the central ray, but, by the opposite effects at the two foci in the transverse pencil, all coma can be destroyed, and the whole field rendered beautifully flat and distinct.[1]

Compound Achromatic Microscopes with Solid and Fluid Lenses.

In 1812, a very simple method was employed by Sir David Brewster, for making both single and compound

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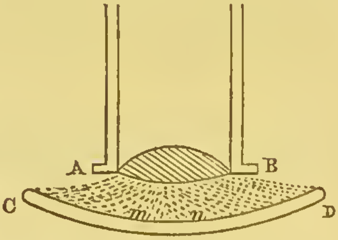
[1] Phil. Trans. 1830, p. 199.

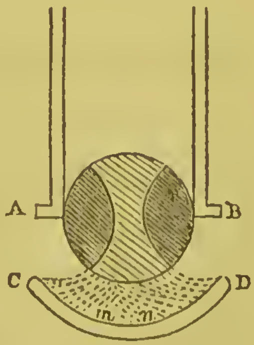
achromatic microscopes. Almost all objects are seen to the greatest advantage when immersed in a fluid, even the finest test objects, such as the scales of the Podura. Having placed the object on a piece of glass, he put above it a drop of an oil having a greater dispersive power than the single lens, or than the concave lens which formed the object-glass of the microscope. The lens was then made to touch the fluid, so that the surface of the fluid was as it were formed into a concave lens. Now if the radius of the outward surface of this lens was such as to correct the dispersion, we have here a perfect achromatic microscope, both simple and compound. The best way is to over-correct the colour of the plate-glass lens by the fluid, and then to reduce the dispersion of the fluid by mixing it with one of a less dispersive power. This will be understood from the annexed diagram, where AB is an unequally convex lens, the flattest side of which is plunged in the fluid *mn*, placed in a watch-glass CD. The object is placed at *mn*, and the dispersion of the concave surface of the fluid compensates that which is produced by the lens. All errors of centring are here removed, and also the loss of light at the touching surfaces of solid lenses. If AB is a single microscope,

Fig. 26.



the object *mn* will be placed in its principal focus, and the emergent parallel rays will enter the eye; but if it is the object-glass of a compound microscope, an image will be formed a few inches behind AB, by withdrawing AB a little from *mn*, or placing the object a little without its principal focus. We have already had occasion to describe an achromatic grooved sphere, but in the process of achromatizing it, the sphere loses in a very small degree its valuable property of refracting in the very same manner all the pencils that enter the eye. This property, however, may be preserved in the bird's-eye sphere by the achromatic method which we have now described. Let AB be the grooved sphere, and CD the watch-glass containing the fluid; it is obvious that every ray which passes through the centre of the sphere will enter and quit it perpendicularly, without suffering any refraction. The same mode of achromatizing the sphere AB may be adopted with a solid concentric concave lens ABCD of flint-glass or other substance, or the sphere may be placed between two such concentric lenses. The greater the dispersion of the flint-glass, the nearer must the outer surface CD approach to AB. By these means the grooved sphere

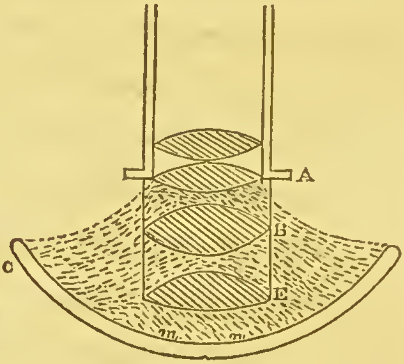
Fig. 27.



may be rendered perfect, both as a single microscope and as the object-glass of a compound one.

The principle above described may be applied to a system of object-glasses like those of Selligues' microscope. Let A, B, E be three convex lenses, so placed at the end of the tube of a compound microscope, that the highly dispersive fluid in the watch-glass CD will enter between the glasses A, B, and E. The concave lenses of fluid will over-correct the

Fig. 28.

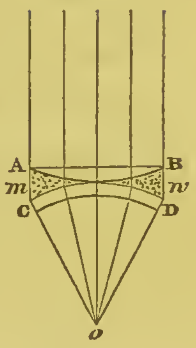


three lenses A, B, and E; but if a very deep curvature on the outside of A is not sufficient to compensate this over-correction, it may be effected by a suitable lens at F. If the three lenses are made of the precious stones, with a high refractive power and a low dispersive one, the concave fluid lenses will not over-correct them.

If we use muriatic acid in the form of butter of antimony, and containing a due quantity of metallic particles, for the fluid, and crown-glass for the lenses, the secondary colours will be completely corrected, and an instrument of the most superior kind produced. If a permanent and portable *aplanatic* object-glass is preferred, the butter of antimony may be placed between a meniscus and a plano-

convex lens of crown glass, as in the annexed figure, where o is the object, CD a meniscus of crown-glass, AB a plano-convex lens, and mn a concave lens of the fluid. This construction of the object-glasses of compound microscopes is much more easily applicable in the case of the microscope than in that of the telescope. In the latter case, the colour of the fluid, the changes which it undergoes by time, and the difficulty of retaining it, are objections of considerable amount; but in the case of the microscope, the colour of the fluid disappears owing to its small thickness, and it may be retained by capillary attraction alone, and renewed as often as we choose.

Fig. 29.



Description of Mr Pritchard's Compound Achromatic Microscope.

This instrument is represented in Plates V. VI. and VII. fig. 21, 22, 23, as fitted up by Mr Pritchard. All its parts are so distinctly shown in the figures that they require no description, especially as the uses of most of the parts have been described in a former chapter. Fig. 21 is a perspective view of the instrument in its most convenient position for examining transparent objects by reflected light. The stops and condensing illuminator, which are

seen under the stage, should be removed when particular objects are viewed. When test-objects are to be viewed by direct light, the instrument can be turned round. Fig. 22 shows the position of the instrument for dissecting. The rest for supporting the hands is shown at *a*, and the large moveable stage at *b*. Fig. 23 shows the proper position of the instrument for viewing opaque objects by the concave reflector *c*. In front of *c*, the object is placed upon a black or white ground, according to its nature; and the light of the candle, collected and thrown upon the mirror *c* by the condensing lens, is again reflected by the mirror upon the object. Fig. 24 is an eye-piece; and fig. 25 represents an apparatus for holding a bottle to show aquatic plants and animals.

In Mr Pritchard's instrument the following are the dimensions and powers of the lenses for a complete microscope.

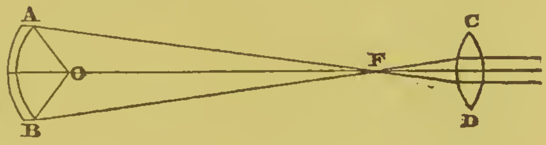
Sidereal Focal Length in Parts of an Inch.	Angle of Aperture.	Magnifying Powers in Diameters by a Standard of 5 Inches.
1	16°	60 to 100
$\frac{1}{2}$	21	100 to 360
$\frac{1}{4}$	42	240 to 500
$\frac{1}{8}$	55	500 to 1100
$\frac{1}{16}$	65	900 to 3000

Of these object-glasses, that whose focal length is $\frac{1}{4}$th of an inch appears to be the most perfect and useful.

Compound Reflecting Microscopes.

Sir Isaac Newton seems to have been the first person who described a reflecting microscope. He communicated his plan to Oldenburg in 1679, as shown in the annexed diagram, where AB is a concave speculum, O the object, F the place where an image of it is formed, and CD an eye-glass for magnifying it.

Fig. 30.



In another letter to Oldenburg, dated 11th July of the same year, he refers to another improvement on microscopes, which is to "illuminate the object in a darkened room, with *the light of any convenient colour, not too much compounded;* for by that means the microscope will, with distinctness, have a deeper charge and larger aperture, especially if its construction be such as I may hereafter describe." We are not aware that this idea was ever further developed by its author.[1]

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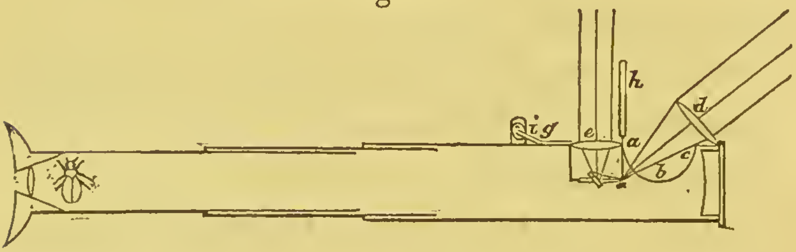
[1] Brewster's Life of Sir Isaac Newton, p. 311.

Mr Potter's Improvement upon it.

Mr Potter[1] has recently described " a new construction of Sir Isaac Newton's microscope," principally with the view of removing the difficulty of illuminating the object. His first construction was for opaque objects; and in order

Fig. 31.



to illuminate them, he cut a large circular aperture *abc* in the tube, between the object and the speculum; but the light which fell on the sides of the tube occasioned a good deal of indistinctness in the field of view. This defect, however, was completely removed by lining all the lower parts of the tube with black velvet. Mr Potter found it advantageous to concentrate the light on those objects that required it, by a large lens at *d*. For transparent objects he applied a lens, as shown at *e*. Its convergent beam is reflected on the object placed at the end of the wire *a*, fixed to a handle *h*, by means of a small diagonal

[1] Edinburgh Journal of Science, Jan. 1832, No. 11, p. 61.

mirror in the axis of the tube, and inclined to this axis 45°. By this means a very strong light may be thrown through and past the object. By means of moveable caps to cover the opening *abc*, and the lens *e*, all interference of foreign light is prevented; and without altering the position of the object, both methods of illumination may be successively adopted. Mr Potter attaches his objects to thin brass pins *a* stuck into wooden handles *h*, and these pins pass through a slit cut into a small piece of cork attached to the sliding piece *g*, which at the same time carries the lens *e* and the plane mirror, the whole of which are moved by the small arm connected to the crank, as at *i*. The adjustment of the object to the focus of the mirror is effected by turning a nut attached to the pivot on which the crank is fixed.

In the microscope used by Mr Potter, he employs a speculum one inch in diameter, with a focal length of $1\frac{1}{2}$ inch; and he generally employs a distance of from 12 to 14 inches between the object and the image.

This size of the speculum allows him to place an insect or other object of $\frac{1}{4}$th of an inch square in the tube, without any perceptible bad effect resulting from it.

When Mr Potter had adjusted the illuminators in the manner which we shall afterwards have occasion to describe, he " saw quite easily what are called the diagonal lines on the scale from the wing of the white cabbage

butterfly, which has been proposed as a difficult test object by Dr Goring; and it is such a one as those who have only seen the stronger longitudinal striæ or scales from the wings of moths and butterflies have little idea of." Mr Potter was also able to resolve a delicate blue tissue in the web of a spider called the *clubiona atrox,* into its component fibres.

The great size of speculum used by Mr Potter arises from his being able to give all his specula a true ellipsoidal figure, so as to remove all spherical aberration.[1] We have in our possession two of Mr Potter's instruments, one of them with a *spherical* and the other with an *ellipsoidal* mirror. The quantity of light and the defining power of the latter are unusual in such instruments.

Amici's Reflecting Microscope.

This instrument is shown in section in the annexed figure, where *a* is a small ellipsoidal speculum about 1 inch in diameter, and $2\frac{6}{10}$ths in focal length. The object is placed on a stage *mn,* below the tube of the microscope, and the rays which issue from it fall upon a small speculum *b* inclined 45° to the axis of the ellipsoidal speculum,

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[1] The process by which he does this is fully described in the Edinburgh Journal of Science, No. 12, p. 228, new series.

in the same manner as if the object had been placed in the tube as far to the right hand of the small mirror as it is below it. An image of this object is of course formed in the other focus of the ellipsoidal speculum, and may be viewed by a single or double eye-piece, as in other compound microscopes. Professor Amici, however, uses a negative eye-piece, consisting of two plano-convex lenses A, B.

Fig. 32.

The new and peculiar part of this instrument is the use of the small speculum, which allows the object to be placed without the tube, and illuminated with the utmost facility. Dr Goring, to whom science is indebted for the perfection of the reflecting microscope, remarks, that "the instrument was turned out of Professor Amici's hands in a rough and ineffective state, owing to the concave metal being of too long a focus and too small an angle of aperture, and the diagonal one (or small mirror *b*, which was half an inch in diameter) of too large a diameter, which caused it to intercept too large a quantity of light from the other, leaving only a narrow rim of reflexion to enter the retina, which occasioned a disagreeable nebulosity in the middle

of the field of view, unless the eye-glass was of great depth."[1]

Dr Goring's Improved Reflecting Microscope.

Mr Cuthbert, an ingenious London optician, constructed one of Amici's instruments, the speculum having $1\frac{1}{2}$ inch of aperture, and a focal length of 3 inches, and the body of the microscope being about 1 foot long. Dr Goring and he having tried it on the test objects which the doctor had newly introduced, found its performance quite unsatisfactory. Dr Goring, therefore, recommended that the speculum should be only half an inch in focal length, and the body 4 or 5 inches long. Mr Cuthbert accordingly finished a pair of metals six tenths of an inch in focal length, and only three tenths in diameter. The excellent performance of this instrument induced Dr Goring and Mr Pritchard to turn their attention to its improvement; and, as Mr Cuthbert[2] has been able to execute perfectly ellipsoidal metals, having an aperture equal to their sidereal focal

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[1] Goring and Pritchard's *Micrographia*, p. 23.

[2] The process by which Mr Cuthbert is able to accomplish this difficult task is similar to that by which he gives truly hyperbolic figures to the mirrors of small Gregorian telescopes, with three inches of aperture and five inches of focal length.

length, or 54°, and of so small a diameter as three tenths of an inch, they have been able to produce an instrument of a very perfect kind.

This microscope is represented in Plate VIII. fig. 26, where the instrument is seen to rest on a tubular pillar, its body being held by a split socket. The pillar is screwed to a solid cruciform stand, to one of the legs of which an adjusting screw is applied, to produce steadiness. The body moves round a cradle joint at the top of the pillar, and may be firmly fixed at any degree of inclination. The body of the microscope is shown at *a*, the eye-tube at *d*, and the eye-piece, which is a Huygenian one, at *e*. The focal lengths of the interior glasses of the eye-pieces, of which there are usually three, are three fourths, three eighths, and three sixteenths of an inch. The tube containing the specula is shown at *bc*. The triangular bar which carries the illuminating reflector, the stage, and the apparatus for adjustment, is shown at *f*, and is soldered to the neck of the body. The mirror *k* is plane on one side, and has a plaster of Paris surface on the other. The stage *l* is a combination of rack and screw work, wrought by two concentric milled heads at *m*. The smallest of these moves the object in the direction of the body, and the other in an opposite direction. The stage can be lifted out of the triangular socket *q*, which carries the adjusting screw *i* for obtaining distinct vision, and the clamping screw *h*.

When the body and stand are used for a compound achromatic microscope, a tube, shown in Plate IX. fig. 27, and containing the compound object-glasses below it, increasing in diameter from the object, is screwed into the body at *b*, in place of the tube *bc*. A rectangular prism, shown in dotted lines, reflects the pencils that pass through the object-glasses along the axis of the tube *bc* to the eye-piece *e*.

The following sets of metals are made for the reflecting microscope.

No.	Solar Focus.	Angle of Aperture.	Distance between Object and side of the Tube.
1	2 inches.	$13\frac{3}{4}$°	$\frac{1}{2}$ inch.
2	1	$18\frac{1}{3}$	$\frac{1}{5}$
3	$\frac{6}{10}$	$27\frac{1}{2}$	$\frac{1}{10}$
4	$\frac{4}{10}$	$36\frac{1}{2}$	$\frac{1}{20}$
5	$\frac{3}{10}$	$41\frac{1}{4}$	almost 0
6	$\frac{3}{10}$	55	

The metals No. 1, 2, and 3 are those most useful for examining opaque objects. No. 3 is excellent also for all kinds of transparent objects. No. 5 can scarcely be used for opaque objects, as it leaves almost no space between the tube and the object for allowing the latter to be illuminated. No. 6 cannot be used at all for opaque objects, but is especially intended for the most difficult class of transparent test objects.

Dr Smith's Reflecting Microscope.

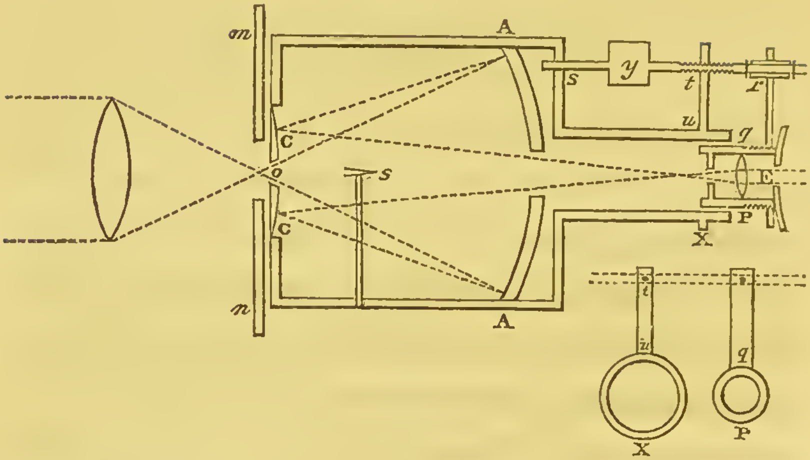
Having constructed one of Sir Isaac Newton's microscopes in 1738, Dr Smith of Cambridge observed that the colours of objects were much more beautiful and natural than in refracting microscopes. He found that objects were very distinct and sufficiently light when the microscope had the following dimensions:—

Focal length of the speculum......................$2\frac{1}{3}$ inches.
Diameter of ditto 1
Focal length of the plano-convex eye-glass......$2\frac{1}{3}$
Ratio of the distance of the object from the focus of the speculum to the focal distance of the speculum ....1 to 19.

Finding that, in order to obtain a high magnifying power, the speculum required to be very concave and small, he contrived another microscope with two reflecting spherical surfaces of any size, but so related to each other that the second reflexion should correct the aberration of the first.

Dr Smith's microscope is shown in fig. 33, where AA is a concave spherical speculum, having its polished convex surface inwards. The rays from an object *o* placed in the slider *mn* will be reflected from the concave speculum AA upon the convex CC, and will have a distinct and magnified image of it formed before the convex eye-glass

Fig. 33.



E, by which it will be magnified still more. This instrument, in short, is nothing more than the Cassegrainian telescope converted into a microscope, with this difference only, that in the telescope distinct vision is obtained by moving the convex mirror, whereas in the microscope it is obtained by a motion of the eye-glass. Dr Smith constructed one of these microscopes, which he found to perform " nearly as well, in all respects, as the very best refracting microscopes ;" and the writer of this article has one of them now before him, which performs wonderfully well, though both the specula have their polish considerably injured. It shows the lines on some of the test objects with very considerable sharpness.

The following are the dimensions, &c. of Dr Smith's reflecting mirror, as given by himself :—

Focal length of both specula............................1·0000

Distance of the centres of both specula...............1·6558

Distance of the image from the centre of the concave speculum..1·1337
Focal length of the eye-glass..........................0·1407
Distance of the eye behind the eye-glass............0·1479
Diameter of the eye-hole...................................0·0190
Distance of the object from the centre of the convex speculum..0·0626
Length of the concave speculum...................15° 49′
Arch of the convex speculum..................... 4° 50′ 49″
Distance of the stop *s* from the object................0·4545
Diameter of the stop *s*...................................0·038
Diameter of the hole in the concave speculum......0·143
Diameter of the hole in the convex speculum........0·049
Magnifying power, the focal length, &c. of the eye being 8 inches...300 times.

The dimensions of the instrument in our possession is very different:

Diameter of the concave speculum...............2·17 inches.
Focal length...2·17
Diameter of the hole in it.........................0·376
Diameter of the convex speculum................1·03
Diameter of hole in it..............................0·10
Diameter of stop......................................0·13
Distance of stop from hole in convex speculum..0·67
Distance of specula..................................3·80
Focal length of doubly convex eye-glass........0·17

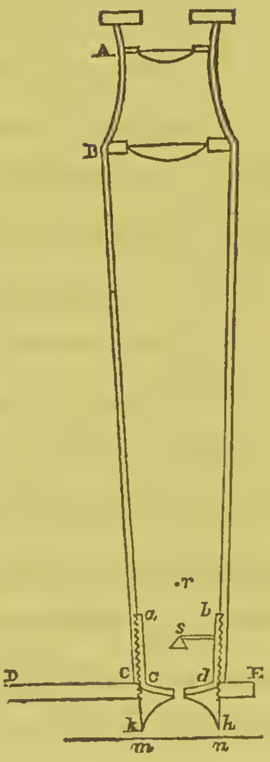
Sir David Brewster's Reflecting Microscope.

Notwithstanding the excellence of Professor Amici's miscroscope, as constructed with Dr Goring's improvements and with Mr Cuthbert's specula, we are quite convinced that it does not owe these advantages to the peculiarity in its construction which constitutes it a different instrument from Newton's. This peculiarity is in our opinion a disadvantage, and we consider the instrument as recommended solely by its possessing an ellipsoidal speculum, with a large angle of aperture. The only advantage which can be ascribed to Amici's instrument is a more convenient mode of illumination, though not much more so than Mr Potter's; but this advantage, whatever be its amount, is purchased at great sacrifices. 1. The whole instrument is an awkward-looking piece of mechanism, with its triangular bar and all its appendages dangling at one end of it. 2. It cannot be used in the vertical position, which we consider a very great defect. 3. By the use of the small reflecting speculum, *more than one half of the whole light is lost.* 4. With small concave specula, such as those $\frac{3}{10}$ths of an inch in diameter, opaque objects cannot be illuminated, as stated by Dr Goring.

The construction which has been proposed by Sir David Brewster to remedy most of these defects is shown in the

annexed figure, where ABC is the body of the instrument, which screws at its lower end C into the horizontal projecting arm DE of the stand, either of the achromatic microscope or the single microscope, so that we get rid of all trouble about the objects placed at *mn*, and their mode of illumination, as every thing concerning them is the same as in other microscopes. This, we must say, is a great advantage; for neither naturalists nor amateurs are disposed to purchase and use two sets of the extended apparatus necessary for holding, moving, and illuminating microscopic objects. At the lower end C of the body, exactly where the object-glasses of the compound and achromatic object-lenses are placed, is a small tube *abcd*, at the lower end of which is placed the concave speculum *cd*, perforated with a very small hole at its centre, and with its concave surface upwards. Above it is the plane speculum *s*, fixed by a slender arm to the side *bd* of the small tube, and having its diameter a little greater than the perforation in the speculum *cd*. This little tube *abcd* screws into the arm DE, as if it were a micro-

Fig. 34.



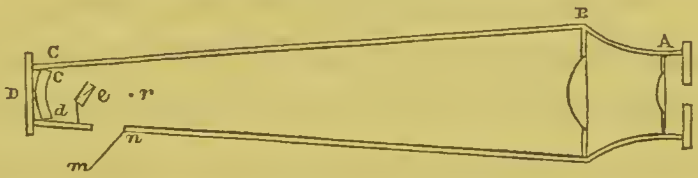
scopic doublet or single lens; and the body ABC may either screw upon the outside of this tube, or, what is better, upon a stronger piece of tube forming part of the arm DE. A concave illuminating reflector *kh*, for opaque objects, may screw on the back of the speculum *cd*, or that speculum may be made thick, and ground and polished on both sides, so that while one side magnifies the objects, the other illuminates them.

It is obvious, that rays proceeding from an object at *mn* will be reflected from the plane speculum *e*, upon the concave speculum *cd*, exactly as if the objects were placed at *r*, as far above *e* as *mn* is below it, and an image of it would be formed in the other focus of the ellipsoid, *r* being the one focus, if the rays were not intercepted by the eye-piece AB, by which the image is farther magnified. By this mode of construction, the whole of the reflecting microscope, in place of having a separate stand and separate apparatus costing a large sum of money, is comprehended in the little tube *abcd*, and may be considered as a reflecting object-speculum, forming part of a general microscope, furnished with single lenses, doublets, and compound achromatics.

By the means now described are removed all the defects which we enumcrated as belonging to Amici's combination, except the *third*, which is one of such importancc that it is of consequence to consider how far it is

capable of being remedied. Sir David Brewster has proposed to get rid of this loss of light by placing the object *mn*, as in Amici's instrument, outside of the tube, but inclined to its axis, and refracting its rays upon the speculum *cd*, by means of an achromatic prism *e*, in a manner analogous to his method of producing a similar effect in the Newtonian telescope.[1] The faces of this prism are equally

Fig. 35.



inclined to the axis of the microscope and the axis of the pencil issuing from the point of the object under examination. As the prisms of plate and flint glass which compose *e* are cemented by a substance of nearly the same refractive power, there will be no farther loss of light than what is reflected at the two surfaces. A socket may be placed at D, for holding an illuminating lens, or the little apparatus for opaque objects, shown in Plate IX. fig. 27. But in order to avoid the encumbrance and expense of separate stands and apparatus for this, as well as Amici's form of the instrument, we would propose that a strong piece of tube should be inserted in the opening, above *mn*, to screw into

[1] Treatise on Optics, Lardner's Cabinet Cyclopædia, p. 354.

the upper side of the projecting arm, as shown in the preceding figure ; or a solid screw attached to the upper side of the tube, a little to the right hand of C, and above the opening, might screw into the lower end of the projecting arm DF. In these cases the object at *mn* will be placed on the ordinary stage, and illuminated in the common manner ; but it will be necessary to have a counterpoise at D, to balance the weight of the body ABC.

Those who are acquainted with the principle of the Cassegrainian telescope, and of Dr Smith's compound microscope, will readily see that the reflecting microscope, with the perforated speculum, may be converted into a more compound reflector, analogous to Dr Smith's, by making the little speculum *e*, fig. 35, convex, the figures of *d* and *e* being made hyperboloids.

CHAPTER IV.

ON POLARISING MICROSCOPES.

The use of polarising microscopes is to observe structures and phenomena which are invisible with the common microscope.

These microscopes were first used by Sir David Brewster, upwards of twenty years ago, in his experiments on the structure of *apophyllite*, *amethyst*, and *analcime*, and other mineral bodies; and also in his examination of various animal and vegetable organizations. In using the single microscope for these purposes, he cemented plates of agate and tourmaline, with Canada balsam, to the plane side of a plano-convex lens,[1] and thus analysed the polarised light, by means of which the peculiar structure was rendered visible. In other cases he preferred for the analyser an achromatised prism of calcareous spar, in which one of the

[1] Edinburgh Transactions, vol. ix. p. 141, note.

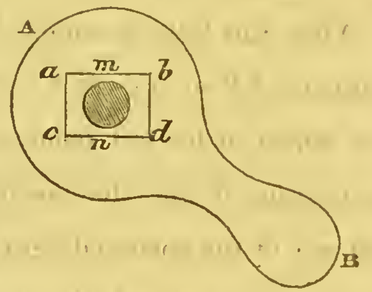
images only was visible,[1] or one in which he had extinguished one of the images by a particular process,[2] which he has described.

When considerable magnifying power was necessary, or when the structure was to be drawn by an artist, he used the compound microscope, in which the light was polarised and analysed by various means, accommodated to the nature of the structure to be examined.

Single Polarising Microscope.

The simplest and most useful polarising microscope is a hand one, such as AB, containing a convex lens *mn*. It is to be held in the right hand, as in the figure, and a plate of light reddish-brown tourmaline, *abcd*, fixed above the lens, either temporarily by a little bit of soft wax, or cemented to it by Canada balsam. The last method has the advantage of preventing the loss of light by reflection from the first surface of the tourmaline, and removing any

Fig. 36.



[1] Edinburgh Transactions, vol. viii. p. 371.

[2] *Ibid.* vol. ix. p. 141, note.

imperfection of polish that it may have. It would be advisable, indeed, to construct the microscope with two plano-convex lenses, and to place the tourmaline between them, and joining it to both by Canada balsam, so that there would be no loss of light or imperfection of vision produced by the surfaces of the tourmaline.

The position of the plate *abcd* should be such, that when it is held as in the figure, the polarised light, which is to illuminate the object, should be unable to pass through it. This polarised light may be obtained either from light reflected, at an angle of 56°, from a plate of black glass, or from a bundle of plates of crown or flint glass, or by transmission through a bundle of such plates, or from one of the images of a rhomb of calcareous spar.

When this light is obtained, the observer holds the microscope AB in his right hand, and examines through it the object in his left hand, turning AB slightly round, so as to bring it into the position when it refuses to transmit any of the polarised light which passes through the object, and towards which, of course, the observer's eye is directed. When this is done, the peculiar structure of the object will depolarise or alter the polarisation of part of the incident light; and this light, being no longer polarised, will pass through the plate of tourmaline to the eye, and exhibit, on a dark ground, and in luminous and often beautifully coloured lines, the structure of the body.

If the body is transparent, and not flat, it may be advantageously placed in a little glass trough, containing water or oil, or a fluid of the same refracting power as the body, so that the polarised light may be made to pass through it in all directions, and exhibit its entire structure.[1]

When the shape and surface of the body present no difficulties, the best method is to stick it by a transparent cement, or simply to place it upon a plate of tourmaline held in the left hand. The observer thus carries the polariser and the object in his left hand, and in his right the magnifier and the analyser.

When a second plate of tourmaline is not at hand, the object may be placed upon a rhomb of calcareous spar, above one of the images which that rhomb forms of a circular aperture on its lower or farther side, the light of the other image being stopped out by a piece of wafer.

When a small lens is needed, and strong light can be commanded, the magnifier and the analyser may be united in one by making the magnifying lens of tourmaline.

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[1] It was in this way, by cementing fragments of crystals of analcime to a piece of wood, and holding the mineral in a small trough of almond oil, that Sir David Brewster detected the extraordinary structure of that substance.

Compound Polarising Microscope.

The simplest form of the compound polarising microscope is to make the eye-glass into an analyser, in any of the ways described for a single lens, the proper position of the plate of tourmaline being readily found by the motion of unscrewing the eye-glass. The polariser is also a plate of tourmaline, laid on the slider-holder, and having the object laid upon its upper surface. If the polariser is laid down in any accidental position, the proper position of the analyser will be found by a slight unscrewing of the eye-glass. The best method is to place the small polarising piece of tourmaline (which need not be larger than an object which fills the field of the microscope) between two pieces of glass, with Canada balsam interspersed. In this way a compound microscope may be converted into a polarising one, fit for any researches, at the expense of a few shillings.

When tourmaline cannot be obtained, the light may be polarised by one or more plates of glass, placed on the illuminating mirror so that their surface may be inclined 34° to the axis of the microscope, and the analyser may be a chip of black, blue, or any other kind of glass, having the reflection from its second surface removed by grinding, or by a few drops of black wax. If this chip is placed on

the brass ring above the eye-glass, so as to turn with that ring, and so that its surface is inclined 34° to the axis of the microscope, the observer, by looking into a little reflector, will see the object under examination when the plane of this analysing plate is at right angles to the plane of the polarising plates.

When the compound microscope is fitted up in the completest manner, and for the express purpose of examining structures by polarised light, which we believe was first done by Henry Fox Talbot, Esq., a Nicol's[1] prism is fixed between the illuminating mirror and the slider-holder, to polarise the light, and another similar prism is placed above the eye-glass. The last prism, however, is very inconvenient, as it contracts unpleasantly the field of view; and it is therefore necessary to substitute for it a plate of tourmaline, as already described.

The expense of constructing a Nicol's prism, the difficulty of making the one next the eye perfectly colourless, and the risk of a change taking place in the cement which

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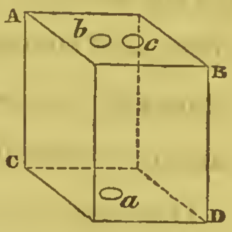
[1] This ingenious prism, consisting of two pieces of calcareous spar cemented together, so as to transmit only one image, derives its name from its inventor, William Nicol, Esq. of Edinburgh, and is of great use in all experiments on the polarisation of light, particularly where the colour of tourmaline would interfere with the phenomena to be observed.

unites the two parts of it, render it desirable to have a simple, a cheap, and a durable substitute for it. The polariser which has been employed by Sir David Brewster in his experiments on elliptical polarisation, and on the action of crystallised surfaces upon light, where tourmaline could not be used owing to its colour, was a single rhomb of calcareous spar, with its natural surfaces having thin plates of colourless glass cemented to them by Canada balsam, which removes any imperfection of surface, and at the same time protects the surfaces from any accidental injury, or from the deterioration of the polish, which arises from frequently cleaning them. This rhomb ABCD had a circular aperture *a*, placed upon its lower surface, and of such a diameter, that it just separated the two images *b c*, seen from above. This rhomb may be placed either beneath the slider-holder, or upon it, and, by sticking a piece of wafer upon any one of the images *b*, *c*, and leaving the other exposed, and placed exactly beneath the aperture of the object-glass, we have the most perfect polariser that can be constructed. The object to be examined may, if necessary, be laid above the circle *b*.

Fig. 37.



By this construction of the polariser, we obtain another advantage; we may so adjust the size and distance of the pencils *b*, *c*, that both of them may be included in the field

of view, and, by placing one of the objects to be examined above *b*, and another of the same above *c*, we may observe them at the same instant under their opposite colours, if the depolarised light is coloured, which it generally is.

These rhombs may be made even out of rhombs crossed with veins, which multiply the images, because the multiplied images are at too great a distance from the principal ones to be visible. This is a peculiar advantage, as it is often very difficult to get good pieces of spar free from this composite structure.

This method of constructing a polarising rhomb enables us to take advantage of the two lateral images, which accompany the two principal images in crystals crossed by one vein. These lateral images, shown at *m*, *n*, are distant from one another, and from the principal images *b*, *c*; and as each of them consists of light wholly polarised in one plane, we have only to bring one of them under the aperture of the object-glass to have an admirable polariser, without being at the trouble of stopping out any of the other pencils.

Fig. 38.

The images *m*, *n*, are much less bright than the principal ones *b*, *c*; but this is really of no consequence, as we can obtain any degree of light we choose in the microscope, either by the condensation of artificial, or the use of solar light.

When the vein by which these lateral images are formed is above a certain thickness, their light is white; but they are most frequently coloured; and the observer who understands the cause of these colours may make this coloured pencil of great service in microscopical observations. If he uses a rhomb which gives to *m* a green of the second order, it will contain none of the extreme violet and blue rays, and none of the extreme red; so that it affords a more homogeneous pencil than if it were white light, and thus improves the performance of a microscope that is not achromatic.

He may in like manner use tints which give the red extremity or the blue extremity of the spectrum, or, even when the tint is divisible by the prism into periodical bands, he may absorb the least luminous of these bands, and create a homogeneous pencil of polarised light of inestimable value, in particular researches, and with particular microscopes.

But, independent of these advantages, the method of using a lateral pencil *m*, has the great advantage of not requiring any thickness in the rhomb. A Nicol's prism, and a rhomb in which the two principal images *b*, *c*, are used, must be about an inch thick in order to be efficacious; but the distances *m*, *n*, or *m*, *b*, are the same at all thicknesses, so that we can use rhombs for this purpose which are quite useless for any other.

It is scarcely necessary to add, that similar rhombs in

which either the principal images b, c or the lateral ones m, n are used, may be employed for the analyser. For this purpose, a thin plate in which m or n is white, is peculiarly applicable, as it enables us to see at once the whole field of the microscope.

CHAPTER V.

ON SOLAR AND OXYHYDROGEN MICROSCOPES.

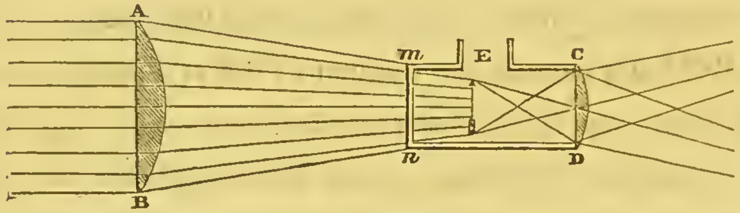
The solar microscope is a well-known popular instrument, for exhibiting on a white screen in a dark chamber, magnified images of minute objects, illuminated by the condensed light of the sun. As the sun cannot often be commanded in our climate, this instrument may be considered as having fallen into disuse; but the discovery of the lime-ball light by Mr Drummond amply supplies the place of the great luminary, in so far as the microscope is concerned. The instrument has accordingly been revived under the name of the oxyhydrogen microscope, and is now a favourite public exhibition.

The solar microscope was proposed by Dr Lieberkhun in 1738; and early in 1739, when he paid a visit to London, he exhibited an instrument of his own construction to several members of the Royal Society, and to Mr Cuff, Mr Adams, and other London opticians.

This microscope is nothing more than a convex lens, in

front of which, a little farther from it than its principal focus, is placed a microscopic object, the rays of the sun being reflected in a horizontal line, and condensed by a lens. This will be understood from the annexed figure,

Fig. 39.



where CD is the convex lens, E the object placed before it, and AB the illuminating condenser. An enlarged image of E will be formed to the right hand of CD, on a wall or screen, and the size of the enlarged image will be to that of the object as the distance of CD from the screen or wall is to CE, the distance of the object from the lens. Dr Lieberkhun's solar microscope had no mirror for reflecting the sun's rays into the tube, so that it could only be used a few hours, when the tube could be conveniently pointed to the sun. The improvement of adding a mirror was made by Mr Cuff, who constructed the instrument in a very superior manner.[1] Dr Lieberkhun subsequently fitted up the solar microscope to show opaque objects ; but

[1] See Baker on the Microscope, vol. i. p. 22.

the method which he employed is not known. Since the time of Mr Cuff, the solar microscope has undergone many improvements. Mr Benjamin Martin added greatly to the value of this instrument, by fitting it up both for opaque and transparent objects, in the manner shown in Plate IX. figs. 28 and 29. In fig. 28 it is shown as fitted up for opaque objects. The body ABCDEF has the part ABCD of a conical, and the part CDEF of a tubular form. A large convex lens, corresponding with AB in fig. 39, is placed at AB, at the end of the conical tube ABCD, which screws into the square plate QR, which is fastened to a window-shutter opposite a hole of at least the size of the lens AB, by means of the screws *e*, *d*. Upon the square plate QR there is a moveable circular plate *abc*. To this circular plate is attached the silvered glass mirror NOP, placed in a brass frame, which moves round a joint PP, and which may be placed in any position with regard to the sun, so as to reflect his rays into the tube ABCD by means of rack-work and pinions at Q and R. The pinion Q moves the circular plate *abc* (to which the mirror NOP is fixed) in a plane perpendicular to the horizon, while the nut R gives it a motion in an opposite plane. The light introduced by this mirror falls upon the lens AB, which throws it in a condensed state upon any object in the tube. But before it reaches the opaque object, it is received by a mirror M, placed in the box HILX, which

reflects the condensed light back upon the face of the object E, fig. 39, next to the lens CD, fig. 39. This mirror is adjusted to a proper angle by the screw S.

Above the body ABEF is seen the part *f*VK which carries the sliders or objects, and the object-glass or lens CD, fig. 39. The tube K slides within the tube V, and V again slides into the box HILX. These tubes carry each a magnifying lens. The inner tube K is sometimes taken out of the other V, seen within the box, and used alone. The sliders and objects are introduced into a slit or opening at H. The brass plate to the left of H is fixed to a tube *h*, by means of a spiral wire within the tube, which presses the plate against the side of the box HILX, so that the sliders, when placed in the opening, are pressed against the side of the box.

In using this microscope, the sun's rays are first made to pass along the tube ABCD, by the nuts Q and R. The box for opaque objects, HILX, is then slid by its tube G into the tube EF. The slider containing the object, having its face to be examined turned to the right hand, is then pushed into the opening at H, till the object is in the centre of the tubes V, K. The condensed light falling on the mirror M is then thrown back on the face of the object in the slider, and the door *ki* shut. Upon a white paper screen or cloth, from *four* to *eight* feet square, and placed at the distance of from six to ten feet from the

window, the observer, in the room made thoroughly dark, will see on the screen a magnified representation of the object, which may be rendered distinct at different distances of the screen, by pulling out or pushing in the tubes V, K containing the convex lenses. As the sun is constantly moving, its rays must be kept in the axis of the tubes by now and then turning the nuts Q and R.

When the microscope is to be used for transparent objects, the box HILX, with its tube G, and other appendages, is removed, and the apparatus shown in fig. 29 substituted for it. This is done by sliding the tube Y of fig. 29 into the tube EF of fig. 28. A slider containing the magnifying lens is then slipped through the opening at *n*, and a second condenser may or may not be inserted in the opening at *h*. The slider with the object is then placed in the opening *m*, and when its magnified picture falls upon the screen, it is adjusted to distinctness by turning the milled nut O.

The picture formed by a solar microscope being in Dr Robison's opinion "generally so indistinct that it is fit only for amusing ladies," he proposed to use as an object-glass the achromatic eye-piece of four lenses, constructed by Mr Ramsden for telescopes. Having made the experiment, he found the image "perfectly sharp," and recommended this application "to the artists, as a valuable article of their trade."

A much simpler method, however, of correcting the defects of the microscope, is to use compound achromatic lenses, which were first suggested by Mr Benjamin Martin.

Another mode of improving the instrument was proposed in 1812 by Sir David Brewster,[1] who has described a new solar microscope, which can be rendered achromatic. The method of doing this is shown in the diagram, fig. 39, where AB is the condensing lens, and CD the object-glass, cemented firmly into one end of a tube *m*CD*n*, which has a tubular opening at E, while the other end of the tube has a circular piece of parallel glass cemented upon it. The tube *m*CD*n* is then filled with water, or any other fluid; and the object, when placed upon a slider, or held in a pair of forceps, is introduced at the opening E into the fluid. The mechanism for producing these effects is easily conceived. By the instrument thus constructed, imperfectly opaque and corrugated objects, rendered transparent, and extended by the fluid medium, may be examined in this microscope, though incapable of being used in any other. Objects may be even dissected in the aqueous tube. Nay, objects preserved

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[1] Treatise on New Philosophical Instruments, p. 410.

in spirits might be exhibited by immersing the bottle, if it is small, in the trough or tube mCDn.[1]

But the most important purpose effected by this form of the instrument is, that it can be rendered perfectly achromatic by using a fluid of higher dispersive power than the glass lens CD, and making the interior curvature of the side CD, which touches the fluid, of that degree of convexity which will convert the fluid into a concave lens capable of correcting the colour of CD. The lens CD may be made most advantageously of fluor spar, which, from its low dispersive power, might form an achromatic combination with water.

Although, in so far as we know, metallic specula have never been regularly fitted up as a reflecting solar microscope for use, yet every person familiar with, and in the habit of using, specula and lenses, must have made the experiment of forming magnified images both in solar and artificial light, with small concave specula. The perfection of these images cannot be doubted; and it has often appeared to us surprising that the optician did not avail himself of such a combination for a solar microscope. Neither the Newtonian nor the Amician form of the instrument of-

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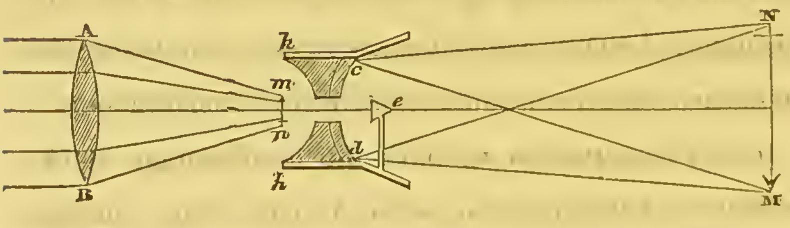
[1] See Treatise on New Philosophical Instruments, p. 401, for an account of the advantages of examining objects immersed in fluids.

fers facilities for this purpose. Sir David Brewster has therefore proposed to employ his form of the reflecting microscope for a solar and oxyhydrogen instrument. Its facilities for this purpose are very great, and there can be little doubt that it will be practically successful, and will be as superior to other solar microscopes as the best reflecting compound microscope is to other compound microscopes. Dr Goring made an experiment with the Amician microscope; but he obviously considers it as not likely to succeed, remarking, that "after all that could be done, a refractor would be sure to beat it hollow; therefore I shall take my leave of the subject, as I cannot conscientiously recommend such an instrument."[1] It is no wonder that this experiment failed, because Dr Goring seems to have used *the whole of the Amician microscope,*

Fig. 40.



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[1] Dr Goring states, that a friend of his had constructed a solar microscope with metals on the Amician principle, and without a body or eye-glass, which exhibited a variety of test objects in a highly satisfactory manner.

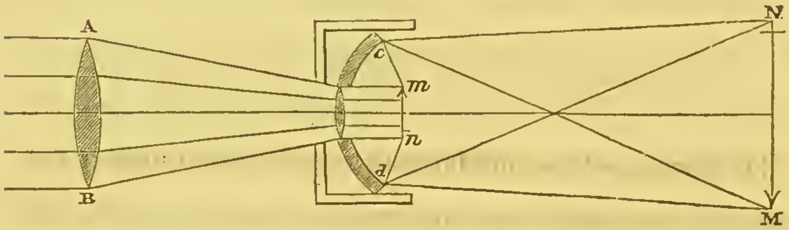
eye-glasses and all, as the magnifier in the solar microscope, and therefore it could not be considered as a *reflecting* solar microscope, being in fact as much a *refracting* one. The construction to which we have above referred is shown in the annexed figure, where AB is the illuminating lens, throwing the condensed rays of the sun upon a transparent object *mn*. The rays from this object falling upon the small speculum *e*, are reflected to the deep concave speculum *cd*, so placed that the image is formed at MN on a screen at some distance behind it, distinct vision being obtained either by moving the object or the speculum.

For opaque objects this form of the instrument is peculiarly adapted. The parallel rays of the sun falling upon the deep speculum *kh*, are condensed by it and thrown on the inner face of the object *mn*, of which a magnified image is formed, as before, at MN. A greater condensation of light may be obtained by using the lens AB, so that the speculum *kh* shall receive its convergent beam before the rays reach their focus and complete their convergency.

In this construction we have the disadvantage of two reflections, belonging also to the Amician form; but this may be considered as compensated by the image being without the tube, and more under our command. Though this is true in the compound microscope, yet the advantage of having the object outside the tube is of less consequence in a solar microscope. To avoid therefore two

reflections, and two mirrors with their relative adjustments, Sir David Brewster has proposed to construct the reflect-

Fig. 41.



ing solar microscope in the manner shown in the annexed figure, where CD is the perforated concave speculum, *mn* the object in one of its foci, and MN the magnified image in its other focus. The object *mn*, placed on a slider passing through an opening in front of the speculum, is illuminated as an opaque object by the lens AB, whose refracted rays are farther condensed by a lens placed in the aperture of the speculum. This form of the solar microscope is therefore singularly adapted for opaque objects; and as the whole of the effect of the instrument is produced by a single reflection from a single surface, it is the simplest optical instrument in existence. In order to throw light upon *mn* as a transparent object, the rays must pass through it in an opposite direction from the side MN, and this may be done by the very same method given by Mr Potter, and represented in fig. 31.

The simplicity and practical value of this instrument will

be immediately recognised by comparing it with the complex opaque box, which in all solar microscopes is a necessary appendage for opaque objects. See Plate IX. fig. 28 and 29.

Dr Goring's Solar Camera Microscope.

Dr Goring, whose indefatigable genius has improved almost all our popular instruments, has described in the *Micrographia* a very complete solar microscope, which has the property of exhibiting the image on a horizontal curved surface, placed in a darkened camera, at which two or more persons can look at the same time. It is in reality a new instrument, but can also be used like the common solar microscope in a darkened room.[1]

This instrument, with all its parts, is shown in Plate X. figs. 30, 31, 32, and 33; fig. 30 being a geometrical elevation of the instrument, *one tenth* of the real size, the

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[1] Dr Goring calls this instrument a *Solar Engiscope*, while he gives the name of *Solar Microscope* to the *same* instrument when used in a dark room in the common way. The introduction of the image into a camera becomes thus the reason for changing a *microscope* into an *engiscope*. The word *engiscope*, however appropriate it may be as a companion to the word *telescope*, is quite inapplicable to any kind of solar microscope.

various parts being represented as if formed of transparent matter. A strong framework A of wood rests upon four legs, having a large hole in it, into which the instrument is fixed with two screws F, F. The frame is large enough to protect the observer from the solar rays. A long plane mirror B is fixed to an arm C, which moves round a pin fixed to the side of the mirror frame, and also round a joint attached to a strong round wire E, which slides backwards and forwards in the tube D, having a spring within, and a pinching nut to fix it in its place. The inclination of the mirror is varied by pulling out or pushing in the mirror, which has also another motion produced by the action of the milled head G on a rack and pinion. A common illuminating lens, five inches in diameter and one foot in focal length, is placed at H. Dr Goring recommends an achromatic lens[1] (which would be a very expensive appendage), though he says that he has never used one. The main body of the microscope is conical, having a bayonet catch at L to receive the rest of the instrument, viz. the tube carrying the stage and rackwork. This tube I I moves within the conical one by means of the milled head M and rack and pinion N. The end of this tube is closed, and an ordinary slider-holder O is fixed to it. On the inner side

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[1] See Edinburgh Journal of Science, No. 9, new series, p. 85; and our chapter on the Illumination of Microscopic Objects.

of the stage, near N, is fixed a condensing lens, about one and a half inch in diameter and two inches in focal length, which, by means of a sliding wire passed through a hole in the stage, can be moved from one side of the tube to the other, and also made to approach to or recede from the stage. A second tube PPP, slit open at the sides, is screwed into the tube in which the stage moves; and into this tube the optical part q is made to slide, the object-glass being placed at K. Dr Goring here remarks, that "the focus may of course be roughly adjusted, by sliding the body backwards and forwards in its containing tube, before it is attached to the camera, fig. 31; but when this has been done, it must of course remain immoveable. I look upon it," he continues, "as a *principle* in the solar microscope, *that the magnifier or object-glass should not be moved, but always remain at a fixed distance from the illuminator.*" Perhaps we do not distinctly understand the import of this passage; but we apprehend that the magnifier or object-glass may be, nay, must be, moved in any way that is necessary to produce distinct vision upon the screen, whatever be its distance; and that the essential condition is, that the distance of the illuminator and the object shall be invariable, the object being, if possible, accurately situated in the focus, unless where a slight deviation is necessary to prevent its destruction by the concentrated heat of the solar rays.

The end of the tube Q is now pushed into another piece of tube at R, fig. 31, which communicates with a conical tube of brass, " having a rectangular prism, with its reflecting side silvered,[1] or a plane metal adjusted at its head S, so as to throw down the image to the bottom of the box or camera, where it is to be received on paper (at T), or on a surface of plaster of Paris duly curved to suit its shape." The camera WWXX is constructed with windows V, V, to permit two persons to view the picture on the table T. Two pieces of wood WW carved out to fill the slope of the upper part of the face, are placed as in the figure (one of them is shown separately in a plan at fig. 33). Dr Goring adds, that " he has found it necessary to exclude the breath from entering the camera, as it dims the eye-glass of the engiscope, and thus spoils the image;" but he does not mention whether this is the

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[1] Dr Goring is surely mistaken in saying that the side of the prism should be *silvered;* for as *total reflection* commences at 41° 49′ for glass, and takes place at all greater angles of incidence, the light incident at 45° will be totally reflected. But even if the least oblique part of the conical beam should penetrate the reflecting surface (which it cannot do), part of the picture would have the light of silvered reflection, and the other part the *double* light of total reflection, which would never answer. We would prefer a plane metallic speculum to the prism, even if sufficiently homogeneous not to affect the accuracy of the picture.

object of the pieces of carved wood, or whether they are used to keep extraneous light from the eye,[1] which, in so far as the figure indicates, does not appear to be the case.

The sides U, U of the camera may be removed at pleasure, to allow the observer to draw the picture on the table, the light being excluded by some black drapery, while the hand passes through a suitable opening in it. Dr Goring recommends that the whole of the exterior (interior ?) of the conical brass tube and camera should be well blacked, or lined with black silk velvet.[2]

In applying this instrument to opaque objects, the opaque box, shown in fig. 32, is applied to the conical tube in fig. 26 by means of the bayonet catch at L. A plane mirror R, adjusted by the screw S, throws the light of the illuminator to the object O placed in the conjugate focus of the eye-glass K, by means of the milled nut M and screw T, which causes the stage and the object to approach

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[1] In using this, and all other optical instruments where perfect vision is either agreeable or essential, we would recommend the use of the Greenland snow spectacles, cut to suit the individual from a plaster of Paris cast of the eyes, nose, and brow.

[2] Mr Potter found black velvet to be superior to any other blacking for the interior of his reflecting microscope. Edin. Journ. of Science, No. 11. p. 62, new series.

to or recede from the lens K.[1] The stage is formed by a piece of cork covered with black velvet. PP is the tube into which the body *q* of the microscope is inserted, as in fig. 26.

This instrument may be converted into a common solar microscope by unscrewing and removing the tube PP, and placing a simple object-glass in an appropriate mounting at M. The whole apparatus is then removed from the frame A, and screwed to a window shutter in the usual way.

On the Oxyhydrogen Microscope.

The great popularity of the public exhibition made with this instrument has turned the attention of opticians and amateurs to its improvement. Mr Pritchard has written a long and interesting chapter of nearly fifty pages on the subject of solar and oxyhydrogen gas microscopes, in the *Micrographia*, already referred to, and has given a most popular and minute account of all the details of the instrument. These details, to which we must refer our readers,

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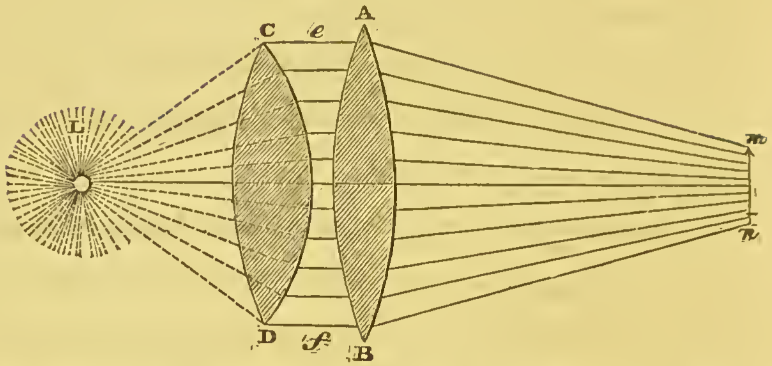
[1] The illumination is here far too oblique. The mirror should be nearer P, and the screw MT should be made to move the object-glass K, in order that the focus of the illuminator may always fall on the object O.

do not belong to an article like the present; and we shall content ourselves with explaining what an oxyhydrogen microscope is, and how the optical apparatus of a solar microscope may be readily converted into that of an oxyhydrogen one, and *vice versa.*

An oxyhydrogen gas microscope differs from a solar one chiefly in this, that a brilliant light obtained by igniting a ball of lime the size of a pea (hence called the *pea* or *lime* light, or more appropriately the *Drummond* light, from its inventor Mr Drummond) with oxyhydrogen gas, is substituted in place of the solar rays. This enables us to enjoy the amusement of the solar microscope apparatus in all weathers and at all hours of the day.

As the lime-ball light, however, is at our elbow, it sends forth diverging rays; whereas the rays of the sun are parallel. A very beautiful principle, already referred to in our article MICROMETER, enables us to give the simplest direction for this purpose. Let AB be the illuminating lens of the common solar microscope, throwing the parallel rays *e f* of the sun upon the object *mn*, and let the whole instrument be in perfect adjustment; then, without moving or changing any part of it, we may convert it into an oxyhydrogen microscope, where the light diverges from the lime-ball L, simply by placing in front of AB another lens CD, whose focal length is equal to the distance of the lime-ball light L from the lens AB. The oxyhydrogen

Fig. 42.



microscope will then have its objects at *mn* illuminated in precisely the same way as they were by the sun's rays. The two lenses CD, AB, should be in contact, the space being left to show the parallel rays *ef*. Now, as L is the focus of the lens CD, the converging rays *ef* will be parallel, and consequently will be refracted by AB, exactly as if they had been the rays of the sun.

If the instrument had been made originally as an oxy-hydrogen microscope, with a large and deep lens at AB, which would be required to refract rays diverging from L to *mn*, then we might convert the instrument into a solar microscope, by simply placing a *concave* lens in front of AB, whose focal distance is equal to the distance of L from AB. This concave lens will give such a divergency to the parallel rays of the sun that they will have their focus at *mn*.

Our readers will find the most ample details respecting the gas apparatus, and the method of managing and using

the instrument, in Mr Pritchard's Essay in the *Micrographia*, already cited.

Notwithstanding the precautions to prevent an explosion of the oxygen and hydrogen employed in this apparatus, we would recommend to Mr Pritchard, and those who may construct such instruments, to use a common lamp, supplied with oxygen gas, such as Sir David Brewster some years ago recommended as a safe substitute for the lime-ball light, when it was proposed to use the latter for light-houses. This oxygen lamp, equally safe and brilliant, has been tried with the most perfect success at the Trinity House, and will, we are confident, be soon in universal use, not only in light-houses, but wherever strong lights are required.

CHAPTER VI.

DESCRIPTION OF MICROMETERS FOR MICROSCOPES.

All the micrometers above described may be adapted to compound microscopes, where the eye-glass has a considerable focal length. A good micrometer, however, for single microscopes, which can be used with facility, and at the same time give accurate results, is still a desideratum. When the single lens is so minute, or when the first lens of a microscopic doublet or triplet almost touches the surface of the object, it is an extremely difficult matter to introduce any scale, or any minute body of known dimensions, with which the object may be compared. In some cases, when the object to be measured is minute, the seed of the *lycoperdon bovista* or *puff-ball* might be introduced, its diameter being about the $\frac{1}{3500}$th part of an inch; and when the object is less minute, the seed of *lycopodium* may be used, its diameter being $\frac{1}{940}$th of an inch. We may advantageously adopt, in some cases, the method of

Dr Jurin,[1] who introduced into the field small pieces of silver or brass wire, whose diameter he had previously ascertained by coiling the wire round a cylinder, and observing how many breadths of the wire were contained in a given number of inches.

This method of introducing a substance of known dimensions may be carried much farther. We may use all the variety of hairs and wool which have a known diameter; and for this purpose Dr Young's table of substances measured by the eriometer will be of great use. The following are a few of them:

	Diameter in Parts of an Inch.	
Lycoperdon bovista, seed of	8500th	of an inch.
Smut of barley	4600th	ditto.
Silk, fibre of (average)	2500th	ditto.
Human blood, particles of (*Bauer*)	2500th[2]	ditto.
Mole's fur	1875th	ditto.
Goat's wool	1575th	ditto.
Saxon wool	1320th	ditto.
Farina of Laurestinus	1100th	ditto.
Seed of lycopodium	940th	ditto.

The distance of the fibres of the crystalline lens of fishes

[1] Physico-Mathematical Dissertations, p. 45.

[2] We consider this the best measure.

may also be advantageously used, and also the distance of the teeth which unite the fibres. For this purpose, the lens must be well dried, and perfectly hard, so that with a sharp knife we can detach minute portions of any of the laminæ. The thinnest should be used; and as the fibres always taper to the pole, and the teeth become smaller in proportion as the fibres diminish, we must determine the distance of the fibres, and also those of the teeth, at both ends of the laminæ, by the method described by Sir David Brewster in the Philosophical Transactions for 1833, p. 324. The larger lined scales of moths and butterflies may also be used, especially as we can measure the distance of the lines by the coloured spectra which these lines produce.[1] The minute subdivisions in the shells of the infusoria discovered by Dr Ehrenberg, and shown in Plate XIII. fig. 24 and 25, are admirably adapted for micrometrical purposes. These operations will require much dexterity on the part of the observer, and they are recommended only to those who cannot succeed in their measurements by other methods.

An excellent method of measuring microscopic objects,

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[1] The late Mr Pond has observed, that the pale, slender, double-headed scales of the *Pontia* or *Picris brassica*, which taper to a point, and terminate in a brush-like appendage, are of an invariable length, about one-eightieth of an inch.

is to project the image of the object against a divided scale, at a given distance from the eye. The scale must be seen either by the same eye which is looking into the microscope, or by the other eye. In the first case, the rays from the microscope will enter one side of the pupil, and the rays from the divided scale the other side; the aperture through which we look at the scale, and the aperture of the microscope, being at a distance less than the diameter of the pupil. When the right eye looks at the divided scale, the left, which looks into the microscope, will see the object projected against the scale, although it has no vision of the scale itself. This second method may be carried into effect in two ways. The scale may form no part of the instrument, and may be viewed by the naked eye; or it may form part of the instrument, like a binocular telescope, the left eye looking into one tube, viz. the microscope, while the right eye looks into another tube, in which a divided scale is magnified by an eye-lens.

Dr Wollaston has constructed and used a very ingenious micrometer on the first of the principles above mentioned, viz. when the object and the scale are viewed by the same eye; but its use is limited to microscopes with small lenses. When the lenses are larger, we have adopted another method, namely, to perforate the lens with a small hole in or near the centre, or, if it is thought better, near the margin of the lens. A slit extending from the margin of the lens may often be executed more easily.

The following is Dr Wollaston's own description of this instrument:

"This instrument," says Dr Wollaston, "is furnished with a single lens of about $\frac{1}{12}$th of an inch focal length. The aperture of each lens is necessarily small, so that when it is mounted on a plate of brass, a small perforation can be made by the side of it in the brass, as near to its centre as $\frac{1}{25}$th of an inch.

"When a lens thus mounted is placed before the eye for the purpose of examining any small object, the pupil is of sufficient magnitude for seeing distant objects at the same time through the adjacent perforation, so that the apparent dimensions of the magnified image might be compared with a scale of inches, feet, and yards, according to the distance at which it might be convenient to place it.

"A scale of smaller dimensions, attached to the instrument, will, however, be found preferable, on account of the steadiness with which the comparison may be made; and it may be seen with sufficient distinctness by the naked eye, without any effort of nice adaptation, by reason of the smallness of the hole through which it is viewed.

"The construction that I have chosen for the scale is represented in Plate XI. fig. 34. It is composed of small wires about $\frac{1}{50}$th of an inch in diameter, placed side by side, so as to form a scale of equal parts, which may be with ease counted by means of a certain regular variation of the lengths of the wires.

"The external appearance of the whole instrument is that of a common telescope consisting of three tubes. The scale occupies the place of the object-glass, and the little lens is situated at the smaller end, with a pair of plain glasses sliding before it, between which the subject of examination is to be included. This part of the apparatus is shown separately in fig. 37. It has a projection, with a perforation, through which a pin is inserted to connect it with a screw, represented at *b*, fig. 36. This screw gives lateral motion to the object, so as to make it correspond with any particular part of the scale. The lens has also a small motion of adjustment, by means of the cap *c*, fig. 36, which renders the view of the magnified object distinct.

"Before the instrument is completed, it is necessary to determine with precision the indications of the scale, which must be different, according to the distance to which the tube is drawn out. In my instrument, one division of the scale corresponds to $\frac{1}{10000}$th of an inch when it is at the distance of 16·6 inches from the lens; and since the apparent magnitude in small angles varies in the simple inverse ratio of this distance, each division of the same scale will correspond to $\frac{1}{5000}$th at the distance of $8\frac{3}{10}$ inches; and the intermediate fractions $\frac{1}{6000}$, $\frac{1}{7000}$, &c. are found by intervals of 1·66 inch, marked on the outside of the tube. The basis on which these indications were founded in this instrument was a wire, carefully as-

certained to be $\frac{1}{200}$th of an inch in diameter, the magnified image of which occupied fifty divisions of the scale when it was at the distance of 16·6 inches; and hence one division $= \frac{1}{50 \times 200} = \frac{1}{10000}$. Since any error in the original estimate of this wire must pervade all subsequent measures derived from it, the substance employed was pure gold drawn till fifty-two inches in length weighed exactly five grains. If we assume the specific gravity of gold to be 19·36, a cylindrical inch will weigh 3837 grains; and we may hence infer the diameter of such a wire to be $\frac{1}{200}$th of an inch, more nearly than can be ascertained by any other method.

"For the sake of rendering the scale more accurate, a similar method was, in fact, pursued with several gold wires of different sizes, weighed with equal care; and the subdivisions of the exterior scale were made to correspond with the average of their indications.

"In making use of this micrometer for taking the measure of any object, it would be sufficient, at any one accidental position of the tube, to note the number on the outside as denominator, and to observe the number of divisions and decimal parts which the subject of examination occupies on the interior scale as numerator of a fraction, expressing its dimensions in proportional parts of an inch; but it is preferable to obtain an integer as numera-

tor, by sliding the tube inward or outward, till the image of the wire is seen to correspond with some exact number of divisions, not only for the sake of greater simplicity in the arithmetical computations, but because we can by the eye judge more correctly of actual coincidence than of the comparative magnitudes of adjacent intervals. The smallest quantity which the graduations of this instrument profess to measure, is less than the eye can really appreciate in sliding the tube inward or outward. If, for instance, the object measured be really $\frac{1}{9900}$, it may appear $\frac{1}{10000}$, or $\frac{1}{9800}$, in which case the doubt amounts to $\frac{1}{50}$th part of the whole quantity. But the difference is here exceedingly small in comparison to the extreme division of other instruments, where the nominal effect of its power is the same.

" A micrometer with a divided eye-glass may profess to measure as far as $\frac{1}{10000}$th of an inch; but the next division is $\frac{2}{10000}$ or $\frac{1}{5000}$; and though the eye may be able to distinguish that the truth lies between the two, it receives no assistance within one-half part of the larger measure."[1]

The micrometer microscopes used for reading off the divisions on the graduated limb of astronomical instruments differ in no respect from the eye-pieces of telescopes fitted up with micrometers.

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[1] Phil. Trans. 1813, p. 119.

Notwithstanding the value of the methods described above, the want of a simple micrometer for microscopes of high power is felt by every person who has been practically occupied with this class of researches; and we cannot give a better proof of this than by adducing in support of our opinion the different measures that have been given by able and ingenious observers, of the size of the particles of the human blood.

Dr Thomas Young	1–6060th	part of an inch.
Dr Wollaston	1–5000th	ditto.
MM. Prevost and Dumas	1–4076th	ditto.
Captain Kater	1–4000th	ditto.
Dr Ehrenberg[1]	1–3600th	ditto.
Messrs Hodgkin and Lister	1–3000th	ditto.
Sir David Brewster	1–2556th	ditto.
Dr Jurin[2]	1–1940th	ditto.

[1] In measuring the size of the fossil infusorias recently discovered by himself, Dr Ehrenberg assumes a globule of human blood to be the three-hundredth of a line in diameter, or the three-thousand eight-hundredth of an inch, but of what inch is not mentioned. He does not state whether this measure is taken by himself or not. He reckons the thickness of a human hair as the forty-eighth of a line at its mean thickness, or the five-hundred and sixty-seventh of an inch.

[2] This result was confirmed by Leeuwenhoeck, who used the same wire, which was sent to him by Dr Jurin. Phil. Trans. No. 377.

Mr Bauer's best observation.....1–2500th part of an inch.
next best............1–2000th ditto.
worst observation...1–1000th ditto.

The three measures of 1000, 2000, and 2500, have been recently given by Mr Bauer himself, as the different steps which he made towards what he conceives the best measure, viz. 1–2500th, which he obtained repeatedly with an improved achromatic microscope. As Dr Young obtained his measure *eriometrically*, namely, by measuring the diameter of the first red ring produced by looking through the blood at a luminous object, we cannot conceive it possible that he could have committed such a mistake as to make the diameter of that ring nearly *thrice as great* as it should be, according to Mr Bauer's results, or more than thrice as great as the concurring measures obtained by Jurin and Leeuwenhoeck. The only explanation we can give is, that the particles of the blood must have an organized structure, or consist of portions separated by lines which have the magnitude assigned by Dr Young. In order to submit this explanation to the test of experiment, Sir David Brewster examined the particles of blood a few minutes after it was drawn, when dried by natural evaporation on a plate of glass. Each particle he found to consist of a dark rim, within which is a bright circle, then a darkish central spot, which spot in some globules may be resolved into a dark ring, a bright ring within this,

and then a small central black spot. Here, then, is the cause of Dr Young's mistake. The red ring of light which he measured in the eriometer was not that which was due to the globule as a whole, but to the parts of the globule. Being anxious to obtain more complete evidence of this fact, we placed lycopodium powder beside the globule of blood, and found that the diameter of the globule was to that of the lycopodium seed as 5 to 18. We then compared the diameter of the red ring produced by the seed with the diameter of the red ring produced by divisions on steel, in which there were 1250 to the inch, as executed for us by the late Sir John Barton, and found the diameter of the seed to be the 697th of an inch. We compared it also with the ring produced by divisions of which there were 625 to the inch, and found its diamcter the 717th part of an inch. The mean of these two is the 710th[1] part of an inch, which, increased in the ratio of 5 to 18, gives the 2556th part of an inch as the measure of the diameter of the globules of blood, agreeing almost exactly with the recent measure of Mr Bauer.

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[1] Dr Young makes this the 940th of an inch, but he has certainly committed a mistake in his observation.

CHAPTER VII.

ON THE ILLUMINATION OF MICROSCOPIC OBJECTS.

The methods of illuminating mieroseopie objeets that have been long in use have been deseribed in the preeeding ehapters. They eonsist in throwing light upon the object, either by means of a mirror or a lens, or both combined; but the nature of the light employed, the magnitude of the peneil, its condition with regard to parallelism, divergeney, or eonvergeney, and the diameter of the pencil employed, or the direetion in which it falls upon the objeet, have never been discussed as matters of science, and upon which the performanee of the finest instrument essentially depends.

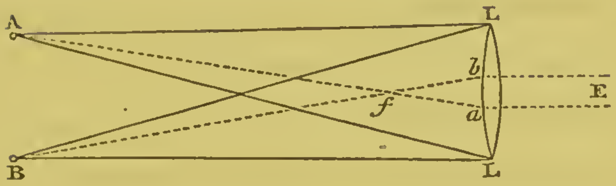
In so far as we know, the most important of these topics was pressed upon the notiee of the seientifie reader by Sir David Brewster, in the year 1820; and in order that the progress of improvement in this essential braneh of the art of making discoveries with the microseope may be understood, we shall quote his observations on the subject.

"The art of illuminating microscopic objects is not of less importance than that of preparing them for observation. No general rules can be given for adjusting the intensity of the illumination to the nature and character of the object to be examined; and it is only by a little practice that this art can be acquired. In general, however, it will be found that very transparent objects require a less degree of light than those that are less so; and that objects which reflect white light, or which throw it off from a number of lucid points, require a less degree of illumination than those whose surfaces have a feeble reflective force.

"Most opticians have remarked, that microscopic objects are commonly seen better in candle-light than in day-light; a fact which is particularly apparent when very high magnifying powers are employed; and we have often found that very minute objects, which could scarcely be seen at all in day-light, appeared with tolerable distinctness in candle-light. So far as we know, the cause of this has not been investigated; and as it leads to general views respecting the illumination of microscopic objects, we shall consider it with some attention.

"Let LL, fig. 43, be a single microscope placed before the eye at E, and let *f* be a microscopic object placed in its anterior focus, and illuminated by two candles at A and B. As the rays *Afa* and *Bfb* cross at *f*, the focus of pa-

Fig. 43.



rallel rays, and as the two shadows of the microscopic object will be formed at *a* and *b*, as it were, by rays diverging from *f*, the images of these two shadows formed upon the retina will coincide and make only one image, so that the object *f* will appear perfectly distinct. If the object, however, is placed either within or without the focus *f*, its shadows being formed, as it were, by rays diverging from a point either within or without the principal focus *f*, will not coincide on the retina, but appear to form two images, either overlapping each other, or completely separated. If, instead of two candles, A, B, we have four, five, or six, we shall have four, five, or six overlapping or separated images. Now, as it is impossible to place the different parts of a microscopic object exactly in the focus *f*, and as every lens has different foci for the differently coloured rays, and even for homogeneous light, in consequence of its spherical aberration, it necessarily follows, that when microscopic objects are illuminated by light proceeding from several points, the image upon the retina must consist of a number of images not accurately coincident; and hence it becomes of the greatest importance that

the object be *illuminated only from one point*, and not from a large surface of light, such as the sky, which is equivalent to an infinite number of radiant points.'

"The following rules may therefore be laid down respecting the illumination of microscopic objects, and the method of viewing them.

"1. The eye should be protected from all extraneous light, and should not receive any of the light which proceeds from the illuminating centre, excepting that portion of it which is transmitted through or reflected from the object.

"2. Delicate microscopical observations should not be made when the fluid which lubricates the cornea of the observer's eye happens to be in a viscid state, which is frequently the case. See Brande's *Journal*, vol. ii. p. 127.

"3. The figure of the cornea will be least injured by the lubricating fluid, either by collecting over any part of the cornea, or moving over it, when the observer is lying on his back, or standing vertically. When he is looking downwards, as into the compound vertical microscope, the fluid has a tendency to flow towards the pupil, and injure the distinctness of the vision.

"4. If the microscopic object is longitudinal, like a fine hair, or consists of longitudinal stripes, the direction of the lines or stripes should be towards the observer's body, in order that their form may be least injured by the descent of the lubricating fluid over the cornea.

"5. The field of view should be contracted, so as to exclude every part of the object, excepting that which is under immediate examination.

"6. The light which is employed for the purpose of illuminating the object should have as small a diameter as possible. In the day time it should be a single hole in the window-shutter of a darkened room, and at night it should be an aperture placed before an argand lamp.

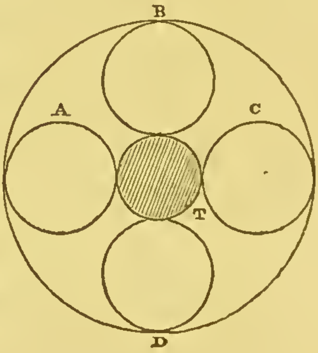
"7. In all cases, and particularly when very high powers are requisite, the natural diameter of the light employed should be diminished, and its intensity increased by optical contrivances.

"8. When a strong light can be obtained, and indeed in almost every case, homogeneous light should be thrown upon the object. This may be done either by decomposing the light with a prism, or by transmitting it through a coloured glass, which has the property of admitting only homogeneous rays."

In the same article Sir David Brewster has described "a new method of illuminating objects in the solar and the lucernal microscopes." "The great defects," says he, "which still attach to the solar and lucernal microscopes, arise from the imperfect method of illuminating the objects. The method suggested by Æpinus, and employed almost universally by opticians, of reflecting the light concentrated by a lens upon the objects, by means of a plane mirror, is good

enough so far as it goes; but in consequence of the light arriving from one direction only, the surface of the illuminated object is covered with deep shadows, and the intensity of illumination is by no means sufficient when the power of the instrument is considerable. We propose, therefore, that in the solar microscope the sun's light should be reflected by a very large mirror through four apertures, A, B, C, D (surrounding the tube T), each of which is furnished with an illuminating lens. The four cones, if condensed, are then received, before they reach their focus, each by an inclined mirror, which reflects them upon the object; the distance of the lens from the mirror, added to the distance of the mirror from the object, being always less than the focal length of the illuminating lens. In the lucernal microscope it would be desirable to place an argand lamp opposite each of the apertures A, B, C, D. By these means the light would *fall upon the surface of the object in four different directions;* a high degree of illumination would be obtained for very dark objects; and by *shutting up one or more of the four lenses, or parts of them, we shall be enabled to find the particular direction of the light which is best suited for developing the structure which it is the object of the observer*

Fig 44.



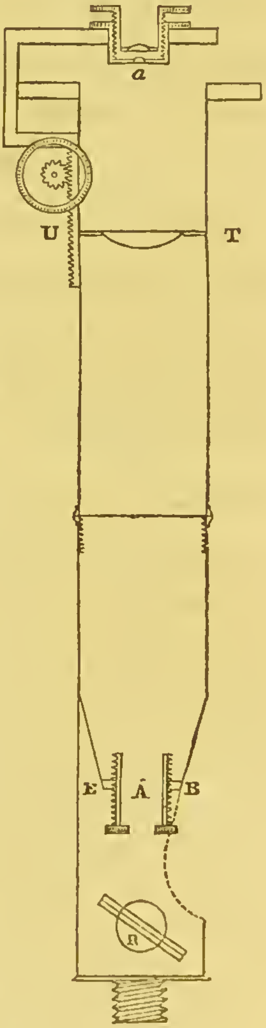
to discover." Although the focus of the illuminating rays should always fall upon the object, for the reasons already assigned, yet in the preceding method, applied to the solar microscope, a deviation from this rule becomes necessary, for *two* reasons: 1*st*, Because, if the focus of the illuminating lens fall exactly upon the object, it might burn it, or destroy it by corrugation; and, 2*dly*, In the ordinary illuminating lenses, the diameter of the focal spot, or image of the sun, is not sufficient to cover the whole object, or to give a sufficient luminous field around it. For these reasons it is recommended in the preceding extract to place the object a little way within the focus of the illuminator, that is, between the illuminator and its focus. But if the object is such that it cannot be injured by the solar heat, or if the illuminator is sufficiently large to give a focal spot capable of filling the field of the microscope, then the object should be placed in the solar focus of the illuminator.

After a lapse of nearly ten years, the subject of microscopic illumination was discussed by Dr Wollaston, in his paper on the microscopic doublet, published in the Phil. Trans. for 1829. This eminent philosopher, whose ingenuity never failed in executing in the best manner whatever he attempted, was then on his death-bed; and this, among other papers, was published without that complete revision which its author would otherwise have given it.

"The state of my health," says Dr Wollaston, "in-

duces me to commit to writing rather more hastily than I have been accustomed to do, some observations on microscopes; and I trust that, in laying them before the Royal Society, they will meet with that indulgence which has been extended to all my former communications.

Fig. 45.



"In the illumination of microscopic objects, whatever light is collected and brought to the eye beyond that which is fully commanded by the object-glasses, tends rather to impede than to assist distinct vision.

"My endeavour has been to collect as much of the admitted light as can be done by simple means, to a focus in the same plane as the object to be examined. For this purpose I have used with success a plane mirror to direct the light, and a plano-convex lens to collect it; the plane side of the lens being towards the object to be illuminated."

These two principles of illumination, the first of which is the same as the first and fifth of the rules already given, though not so fully developed,

and the second founded upon a mistaken principle, have been carried into effect by Dr Wollaston in the following manner:

"T, U, B, E represents a tube about six inches long, and of such a diameter as to preclude any reflection of false light from its sides; and the better to insure this, the inside of the tube should be blackened. At the top of the tube, or within it at a small distance from the top, is placed either a plano-convex lens ET, or one properly curved, so as to have the least aberration, about $\frac{3}{4}$ths of inch focus, having its plane side next the object to be viewed; and at the bottom is a circular perforation A, of about $\frac{3}{10}$ths of an inch diameter, for limiting the light reflected from the plane mirror R, and which is to be brought to a focus at *a*, giving a neat image of the perforation A, at the distance of about $\frac{8}{10}$ths of an inch from the lens ET, and in the same plane as the object which is to be examined. The length of the tube, and the distance of the convex lens from the perforation, may be somewhat varied. The length here given, six inches, being that which it was thought would be most convenient for the height of the eye above the table, the diameter of the image of the perforation A must not, excepting with lower powers than are here meant to be considered, exceed one twentieth of an inch.

"The intensity of illumination will depend upon the

diameter of the illuminating lens and the proportion of the image to the perforation, and may be regulated according to the wish of the observer. * * *

"The lens ET, or the perforation A, should have an adjustment by which the distance between them may be varied, and the image of the perforation be thus brought up to the same plane as the object to be examined. * *

"For the perfect performance of this microscope, it is necessary that the axis of the lenses, and the centre of the perforation A, should be on the same right line. This may be known by the image of the perforation being illuminated throughout its whole extent, and having *its whole circumference equally well defined.* For illumination at night, *a common bull's-eye lanthorn may be used with great advantage.* * * *

"Supposing the plano-convex lens to be placed at its proper distance from the stage, the image of the perforation may be readily brought into the same plane with the object, by fixing temporarily a small wire across the perforation with a bit of wax, viewing any object placed upon a piece of glass upon the stage of the microscope, and varying the distance of the perforation from the lens by screwing its tube *until the image of the wire is seen distinctly at the same time with the object upon the piece of glass.*"

In the preceding passages we have extracted every one of Dr Wollaston's observations in reference to his method

of illuminating microscopic objects, so that the reader will be enabled thoroughly to understand it.

This method of illumination was highly commended by optical writers. Dr Goring[1] considered it as most effective, and enumerates it among the inventions which founded a new era in the history of the microscope; and he elsewhere states, that "there is no modification of daylight illumination superior to that invented by Dr Wollaston."[2]

The marked difference between the methods of illumination proposed by Dr Wollaston and Sir David Brewster, induced the latter to publish, in 1831, a paper "On the Principle of Illumination of Microscopic Objects."[3] In this paper the mistake committed by Dr Wollaston is clearly pointed out. The rays which Dr Wollaston throws upon the object, in place of being *rays actually converged to a focus*, as they ought to be, are rays which diverge from a focus situated between the object and the lens. He makes the focal point of the circular margin of the perforation fall upon the object, without considering that the rays which pass through that perforation do not diverge from it, and therefore cannot be collected in the conjugate focus cor-

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[1] Microscopic Illustrations, Exord. p. 1, Lond. 1830.

[2] Microscopic Cabinet, p. 181, Lond. 1832.

[3] Edinburgh Journal of Science, new series, No. 11, p. 83.

responding to the perforation. In Dr Wollaston's diagram (Phil. Trans. 1829, plate ii. fig. 1), the rays which are incident on the mirror R are actually drawn as parallel rays; and it is quite clear that he meant them to be parallel rays issuing from the bull's-eye lanthorn, which he recommends. But if we suppose that a common flame is used, the error is just of the same nature. It is a distinct image of the *flame* that should be thrown upon the object; and hence the perforation A should be placed close to the flame,—the source of light and the illuminated object forming the conjugate foci of the lens. After explaining this principle, Sir D. Brewster adds in the same paper:—"I have no hesitation in saying, that the apparatus for illumination *requires to be as perfect as the apparatus for vision*; and on this account I would recommend *that the illuminating lens should be perfectly free of chromatic and spherical aberration, and that the greatest care be taken to exclude all extraneous light, both from the object and from the eye of the observer.*"

At the meeting of the British Association at York in 1831, the preceding methods were communicated to Mr Potter, who was then engaged in inquiries with the reflecting microscope, and who had used only the common method of illuminating his objects. The effect which he obtained by it is thus described.[1] "I am indebted to

[1] Edinburgh Journal of Science, new series, No. 11, p. 64.

Dr Brewster for information on the necessity of having the focus of the illuminating lens for transparent objects to fall exactly upon the object, when great nicety of vision is required. Having adjusted my microscope carefully on this point (see our figure, p. 80, where the object is seen in the focus of the illuminating rays), I saw quite easily what are called the diagonal lines on the scale from the wing of the white-cabbage butterfly, which has been proposed as a difficult test object by Dr Goring; and it is such a one as those who have only seen the stronger longitudinal striæ on scales from the wings of moths and butterflies have little idea of." By the same means Mr Potter's instrument "showed him easily not only the striæ on the scales of the wing of the small house-moth, but also the diagonal lines." Mr Potter afterwards applied his microscope, and the new method of illumination, to "a much more difficult object than those just referred to." This object is the broad bluish band first noticed in the web of the spider, the *Clubiona atrox*.[2] "There can be no doubt," says Mr Potter, "that this blue band consists of lines produced by the spider, and woven into the delicate tissue. To demonstrate these fibres, however, is a work for an expert microscopist, provided with a first-rate instrument. So critical

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[2] It is found in the crevices of old walls, and may be recognised by its irregular fleecy-looking web.

a defining power is required, at the same time with a large quantity of light, that I doubt much whether any compound refracting microscope, even the best achromatic, will ever show the construction of this web on a transparent object. When viewed in this manner through good common compound microscopes, the blue band can scarcely be perceived at all with a moderately high power. It is better seen as an opaque object by the light of the sun, and it was on this method that I discovered it, when highly illuminated and highly magnified, to be covered very regularly and closely with white spots. This was sufficient information that it was of an uniform texture; but as there is always in such a light a strong display of irradiations and prismatic colours, it was impossible to trace the fibres. I had discovered something of the texture with small globules of glass, used after the manner prescribed by Leeuwenhoeck; but with very high powers the distinct field of view is so small, that I dared hardly to pronounce decidedly upon the general structure; *and it was only after adjusting the illuminating lens of my microscope very carefully, that I saw with it the complete structure of a regularly woven net.*"[1]

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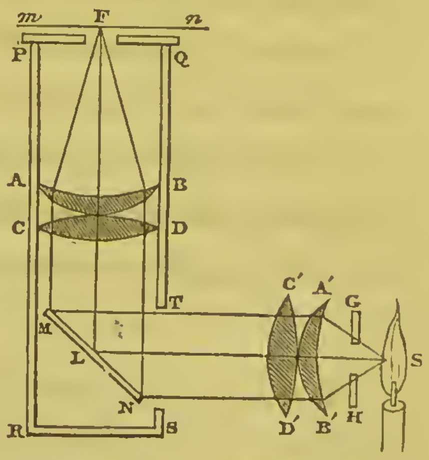
[1] Mr Pritchard received from Mr Potter a specimen of this web; but though he detected the *blue* bands, yet, as the specimen was not a recent one, he was unable to perceive "the complete structure of a regularly woven net." (*List of* 2000 *Microscopic Objects*, p. 6, 7.)

After this strong testimony to the practical utility of Sir David Brewster's method of illumination, and the unquestionable optical principles on which it is founded, we were surprised to observe that Dr Goring and Mr Pritchard should, in the Microscopic Cabinet, published in 1832, still recommend and use a method so decidedly erroneous in theory, and founded on no optical principles whatever. Dr Goring has described what he calls an improved illuminator, which is just Dr Wollaston's, with a stop in the focus of the lens.

As the progress of discovery with the microscope must depend upon the scientific illumination of the objects under examination, we shall proceed to describe, in detail, the method of illumination used by Sir David Brewster. Let *mn* be the plane surface on which the object rests accurately perpendicular to the axis of the lens, lenses, or mirrors, which constitute the microscope. Let PQRST be a tube from one and a half to two inches long, and wholly lined with black velvet.

Fig. 46.



This tube has an opening at ST, and must be so attached by an universal joint, or any analogous contrivance, to the

slider-holder, that the axis FL of the tube can be inclined at any angle to the surface *mn* from 90°, its general position, to 60° or less, as circumstances may require. It should also have a circular motion about its axis, in order that the inclination may be made in any azimuth. A doublet AB, CD, of no aberration, and having a focal length of from half an inch to an inch, is then placed in the tube, with a rack and pinion, or any other adjustment, to bring its focus for parallel rays F, or its conjugate focus for diverging rays, accurately to a point in the plane *mn*, and upon the object lying in that plane, for examination. A short way below it is placed a metallic speculum (not a silvered glass one), which receives parallel or diverging rays, entering the tube at ST, and reflects them upon the doublet ABCD. This speculum should be of pure virgin silver, notwithstanding its liability to tarnish, and should be wrought with the same care as the plane speculum of a Newtonian telescope; or it might be a rectangular prism of good homogeneous glass, acting by total reflection. This part of the illuminator forms part of the microscope.[1] The other part of the illuminator, which is detached, is no less essential. It consists of the flame S, which should

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[1] If the axis of the microscope is placed horizontally, or even with some obliquity, we may dispense with this speculum altogether, and direct the tube at once to the illuminating flame.

be as bright and small as will give the necessary quantity of light after condensation. As close to it as possible is placed a stand for holding a screen, with different circular apertures, and a variable rectilineal aperture. If a stronger light is required than can be obtained from the plane S, its light must be condensed into a parallel beam SL, by another doublet of no aberration, A′B′C′D′, the flame S being in its anterior focus.

The illuminator, as now described, is adapted to homogeneous light, either as obtained from a monochromatic lamp, or by means of coloured glasses, or from the prismatic spectrum; but if we employ common light, the doublets ABCD, A′B′C′D′ must be achromatic. We have mentioned above a variable rectilineal aperture. This is a most essential accompaniment for giving perfection to the vision of lined objects. The aperture should be made to form every possible angle with a vertical line, and should be opened and shut by means of a screw, till as much light is introduced as is necessary to obtain a perfect view of the object. The image of the slit, which is close to the flame, must be thrown upon *mn*, so as to be parallel with the lines of the object. When the objects are circular, circular apertures are preferable to any other.

We have already stated that no light should reach the eye, either from the field of the microscope, or any other source. For this reason it would be desirable to have cir-

cular and rectilineal apertures of different sizes, to be placed immediately beneath *mn*, so as to allow no part of the field to be seen, excepting that which is occupied by the object or part of it under examination.

The above apparatus being provided, let us suppose that the observer is called to examine some structure very difficult to be resolved, such as the blue band of the *Clubiona atrox*, or the structure and nature of the lines on test objects. We omit at present the consideration of the preparation of the object and the eye of the observer, and also the nature of the light which he is to use, as these will be separately considered; and confine ourselves to the use of the illuminator. The object is first placed on a piece of thin colourless parallel glass, or film of topaz or sulphate of lime, near its middle, and the microscope is directed to it, so that it can be seen distinctly in the ordinary way. Put the illuminator in its place, and set the proper aperture close to the small plane. Adjust the doublet ABCD by its screw or pinion till a distinct image of the aperture GH is seen in the field; and, by means of the apertures below *mn*, any strong or unnecessary light may be still more completely excluded. If the structure is not rendered sufficiently distinct by this process, it will be proper to try the effects of oblique illumination, by inclining the axis FL of the illuminator to the plate *mn*, and observing carefully the effects which it produces in different azi-

muths. If all these means are insufficient, we must have recourse to new auxiliaries,—to monochromatic light if the microscope is not achromatic, or to monochromatic illumination if it is achromatic ; and we must prepare both the eye and the object, the one for exhibiting and the other for viewing to the best advantage the structure which we are anxious to develope. These important topics we shall treat in their order, and with as much brevity as possible.

CHAPTER VIII.

ON THE MONOCHROMATIC ILLUMINATION OF MICROSCOPIC OBJECTS.

If a simple and easily applied system of monochromatic illumination, that is, of illuminating objects with homogeneous light, which a prism, and consequently a lens, is not capable of dispersing or refracting in different directions, could be contrived, we should never again hear of compound achromatic microscopes. We believe it will be admitted, that in Sir John Herschel's doublet of no aberration, the spherical aberration is more completely corrected than in any double or even triple achromatic object-glass. Hence it follows, that in homogeneous light such a doublet would be a better microscope than the compound lens. But in the best system of achromatic compensation that can be executed, the secondary spectrum still remains without a remedy; and hence the doublet of no aberration, in which there can be no secondary colour in homogeneous light, must be a superior instrument to the compound achroma-

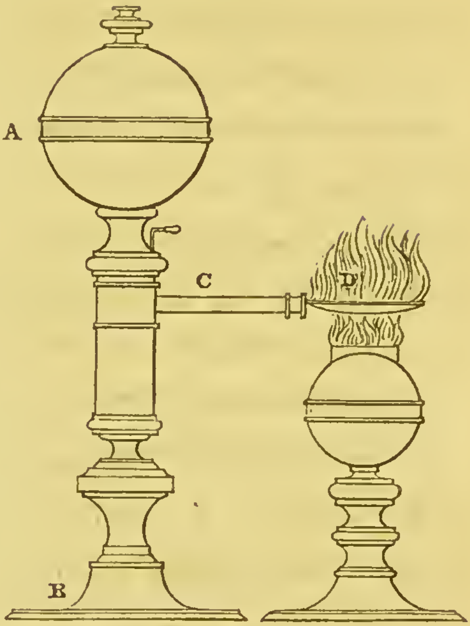
tic lens. Now, in telescopes it is impossible, except in viewing the sun's disc,[1] to work with homogeneous light; but in microscopes, where the quantity of light is in our power, it is perfectly practicable to make that quantity so great that all the yellow or red rays which it contains may give sufficient light for microscopical observations. This insulation of homogeneous light may be effected in two ways; 1*st*, by a monochromatic lamp, as proposed and constructed by Sir David Brewster; 2*dly*, by the absorption of coloured media; and, 3*dly*, by the prism.

The monochromatic lamp is shown in the following figure, where AB is a lamp having its globe A filled with diluted alcohol, which descends gradually through the tube C, into a thin platina or metallic cup, in which it burns. A strong heat is kept up by a spirit lamp L enclosed in a dark lanthorn, and when the diluted alcohol is inflamed, it will burn with a fierce and powerful yellow flame. If the flame should not be perfectly yellow, or rather of a *nankeen* colour, owing to an excess of alcohol, a small proportion of salt thrown into the cup D will have the same effect as a farther dilution of the alcohol. Sometimes a little blue light will be found mixed with the yellow,

[1] A solar telescope should never be an achromatic one, but should consist of a compound lens of no aberration, all the colours of the spectrum but one being absorbed by the darkening glass.

but this may be easily absorbed by a piece of yellow glass placed on any part of the microscope through which the rays pass. Although this light is feeble compared with that of white flames, yet, by using larger lenses for condensing it, it is quite easy to obtain a pencil sufficiently powerful for all microscopic observations.[1]

Fig. 47.

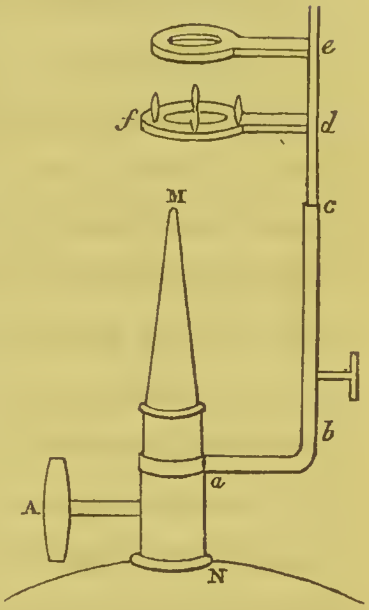


A stronger flame may be produced by using a gas lamp, or, what is still better, a portable gas one containing compressed gas. This gas, when rushing out in a full stream, explodes when burned with atmospheric air, emitting much heat, and a faint bluish and reddish light. As the force of the issuing gas is sufficient to blow out the flame, a contrivance for sustaining it becomes necessary. The method which we contrived for this purpose is

[1] Edinburgh Transactions, vol. ix. p. 435.

shown in the annexed figure, where PQ is the main body of the lamp, MN the principal burner and A the screw, which opens the main cock. A small gas tube *abc*, communicating with the main burner, terminates above the burner, and has a short tube *de* moveable up and down within it, but so as to be gas light. This tube *de*, closed at *d*, communicates with the hollow ring *fg*, in which four apertures are perforated so as to throw their jets of gas to the apex of a cone whose base is *fg*. When the gas is made to issue from the burner M, it rushes also into the tube *abcdg*, and issues in four small flames at the apertures in the ring *fg*; and the height of these flames is regulated by the stop-cock at *b*. The explosive mixture of air and gas which rushes up through the ring is sustained in combustion by these small flames, through which it passes. A broad collar, made of coarse cotton-wick, and thoroughly soaked in a saturated solution of common salt, is fixed on a ring *h*; and when the bluish flame of the explosive mixture rises above *h*, it will be converted by the salted collar into a

Fig. 48.



strong mass of homogeneous yellow light. A hollow cylinder of sponge, with numerous projecting tufts, may be substituted for the cotton collar, or a collar of asbestos cloth might be used, and supplied from a capillary fountain containing a saturated solution of salt.[1]

When the few blue rays which sometimes mingle themselves with this yellow light are absorbed, every part of the light will be found to have a definite refrangibility, greater than any other artificial light that can be produced. The minutest objects, and the smallest type, will appear perfectly distinct in this light when seen or read through the largest possible angle of the greatest dispersive prism, an irrefragable proof of the perfect homogeneity of the light.

2. The second method of producing homogeneous light, and by far the simplest and most easily applicable to microscopes, is that of absorption; and the best rays to leave unabsorbed or insulated are the red. It requires some experience and scientific knowledge of the action of different absorbing media to select those which will leave the *narrowest and brightest band* of the *red* space in the spectrum. We have now under our microscope (a grooved sphere of garnet executed by Mr Blackie[2]) two scales of a moth ly-

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[1] Edinburgh Journal of Science, new series, No. 1, p. 108.

[2] This sphere, which we have already mentioned, is made of the

ing in sulphuric acid, and covering each other. With solar light the spaces between the lines glitter with all the hues of the rainbow; but when a thickish plate of red mica is combined with another plate of red glass, and placed beneath the object, all these colours instantly disappear, and a perfection of vision is obtained, which can be disturbed only by the very small portion of spherical aberration which must exist in the sphere, and which an increased depth of the groove would render almost insensible. Blue glasses, and green and yellow, as well as coloured fluids, may be successfully used in narrowing the range of refrangibility of the red space.

3. The third method, or that of prismatic refraction, is perhaps the surest and the best method of obtaining homogeneous light with the smallest extent of refrangibility. A certain effect may be produced by small prisms; but in order to have a perfect apparatus, the *microscope should form part of the apparatus for examining the lines of the solar spectrum;* that is, it should screw into the eye-piece of the telescope, in front of the object-glass of which is placed a fine large prism, for forming the spectrum within

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urest garnet, and is executed in the most admirable manner; and though we cannot say that we see any defect in it, yet if the groove were still deeper, both its spherical and achromatic aberration would be diminished.

the telescope. By this method, which we have put to the test of experiment, microscopical observations can be carried on with an accuracy and satisfaction which nothing can exceed. We enjoy the luxury of perfectly monochromatic vision, greater than which the most perfect achromatic compensation cannot give; and while we have the spherical aberration corrected, we have *no secondary colours,* and none of the imperfections of vision which must arise in transmitting light through six or eight lenses of plate and flint glass.

Although we hope that the scientific reader will admit that the preceding views are demonstrably correct, yet Dr Goring has pronounced a most unfavourable opinion of the system of monochromatic illumination.[1] We have already endeavoured to convert him from this heresy, and hoped that we had succeeded;[2] but in the *Micrographia,* just published, he has devoted a whole chapter to the reproduction and support of his former views.[3] We shall therefore again examine his objections in their order, as they obstruct the progress of improvement among those who justly admire Dr Goring's ingenuity and knowledge in every thing which relates to the microscope.

1. Dr Goring's first objection to monochromatic il-

[1] Edinburgh Journal of Science new series, No. 9, p. 52.
[2] *Ibid.* p. 143. [3] Page 73.

lumination is, that it is too weak, and must be about one seventh of the whole beam of light. This we are not disposed to dispute ; but Dr Goring is too well acquainted with the resources of optical science, to forget that this monochromatic seventh of a beam of light may be made *seven* times more intense than the whole beam. The objection, however, does not apply to the solar spectrum, for one seventh of the sun's light is too intense for any eye to bear.

2. The second objection of our author is, that the colours of the spectrum, when separated by the prism, are actually separated into different colours when they are refracted in oblique pencils by a microscope. If this observation is correct, then we must denounce the prism that produced such a spectrum as utterly useless. Dr Goring, however, conceives his observation and his prism to be good, and endeavours to explain the result by referring to Sir David Brewster's analysis of the spectrum, in which it is shown that white light exists at every point of it ; but this white light, which has been rendered visible by absorption, cannot be decomposed by refraction of any kind, as it consists of red, yellow, and blue rays, of the same refrangibility. Such white light is the light that is wanted for the microscope ; and there can be little doubt that absorptive media will yet be discovered to effect its insulation in sufficient quantity for practical purposes.

3. Another objection to monochromatic light is, that it will not show the real colours of microscopic bodies. This is true ; but the object of the microscope is not to find out colours, but structures. A common glass lens, with common light, will let the observer have all that he wants of the colours of objects ; and when he has learned this, he will then gladly avail himself of coloured light for more important purposes. We can truly say, that though we have wrought with the microscope for thirty years, we do not at present recollect a single case where we required to know any thing of the precise colours of minute bodies. Notwithstanding this discussion, Dr Goring concludes his chapter with the following observation, in which we entirely concur. "A monochromatic light, therefore, being once obtained *in a sufficient state of intensity for practical purposes,* bids fair to conduct us to the highest perfection of which aplanatic object-glasses and magnifiers are susceptible." It may be proper to add, that the best system of compound achromatic object-glasses now in use would be freed of all their secondary colours, by using monochromatic light ; and they may be also greatly improved, by employing suitable coloured media to absorb what are called the outstanding rays in an achromatic combination.

CHAPTER IX.

ON THE PREPARATION OF THE OBJECT AND THE EYE FOR MICROSCOPICAL OBSERVATIONS.

In using lenses of short focus, either singly or in doublets and triplets, the object is so near the lens, and its thickness, even when very small, forms such a considerable part of its distance from the nearest refracting surface, that any bend or want of flatness in the object completely interferes with the distinct vision of its parts. When the object will bear pressure, the best way is to lay above it a thin transparent film, with perfectly parallel and polished surfaces, such as a splinter of New Holland topaz, a thin plate of sulphate of lime, or a film of mica. If these plates are a little less thick than the distance between the lens and the object, a little bees' wax should be interposed between the brass setting of the lens and the plate, so that the lens in the act of adjustment would press the wax against the plate, and the plate against the object, till distinct vision is obtained. The object should be placed upon a deeply curved concave surface.

The proper flattening of the object, when it is tender, may be effected by pressing a thick balsam above it, and allowing the lens to dip into the balsam. If the surface of the lens is flat, its magnifying power will suffer no diminution.

When grooved spheres are used, such as the garnet one above mentioned, the object requires to be very near its surface. It should therefore be placed in a concave lens of glass, of a little greater radius than the sphere, and pressed into the concave form by interposing a narrow strip of a thin film of mica, and, if necessary, pieces of wax or India-rubber, as before; the pieces filling up the space between the lens and the mica, so as not to interfere with the part of the object under examination.

If a diminution of the magnifying power can be permitted, a fluid may be placed between the concave object-plates and the grooved sphere, and the chromatic aberration greatly reduced. By the interposition of a fluid a grooved diamond sphere may be used; for though its focus for parallel rays falls within the sphere when the refractions are made from air and into air, yet when the first refraction is made from a suitable fluid, the focus will fall without the sphere.

When the object is put into the best possible condition for observation, and the illuminator applied in the best possible manner, the observer will have every advantage

in his researches; but still the structure which he seeks to develope may escape his eager research. Under these circumstances, he must perform his part of the observation in the best possible manner.

Unless particular arrangements are made by the observer for his own comfort, there is no bodily fatigue to be compared with that of the use of the microscope. The eye, the mind, and the whole frame, are on the stretch. The observer must therefore first try if his own eye is in a right state for observation. The fluid which lubricates the cornea, which must be considered as a lens, and as part of the microscope, is sometimes in such a viscid state, that when the eyelids roll over the cornea by that beautiful provision of nature by which it is kept smooth and clean, the lubricating fluid, which is pushed into a ridge between the eyelids, does not quickly recover a convex surface. This state of the cornea is incompatible with delicate microscopic observations, and its existence may be ascertained by viewing the expanded image of a luminous point held close to the eye, and, after shutting the eyelids and again opening them slowly, observing if the luminous disc recovers its uniform luminosity quickly or slowly. If the luminous line produced by the fluid accumulated between the eyelids continues to be visible, and the general surface mottled and spotted, the lubricating secretion should be excited by exposing the eye to the va-

pour of hartshorn, raised by pouring a few drops on the surface of boiling water. The secretion will now flow copiously, the cornea will be swept clean by the purer and less viscid fluid, and the vision of the observer greatly improved. But this moveable fluid surface of the cornea generates another imperfection of vision, which has already been referred to. This fluid, when undisturbed by the eyelids, descends by the influence of gravity in vertical lines, and the minute ridges thus formed obliterate and render indistinct all horizontal lines seen by the eye, but have a tendency rather to improve the vision of vertical lines. In proof of this, we may state the unquestionable fact, that if we take a striped pattern of any fabric, and bend part of it into a horizontal direction, while the rest remains vertical, or *vice versa*, the vertical part will always appear the most distinct. Hence, in viewing lined objects, when the position of the observer's head is either vertical or oblique, the lines of the lined object should be always placed parallel to the direction of the descending fluid. If the axis of the lenses is vertical, and the eye looks downwards, the lubricating fluid will collect irregularly at the apex of the cornea, and injure vision. If the axis of the lenses is horizontal, and the observer's head in its natural position, the fluid will descend in vertical lines; but if the observer lies on his back and looks into the microscope upwards, a position, we admit, not favourable for research,

the fluid will flow equally in all directions from the apex to the margin of the cornea, and leave a clear centre well fitted for distinct vision. We may here notice the beautiful contrivance, not mentioned by natural theologians, that the effect of vertical descent of the lubricating fluid is counteracted by the eyelids opening horizontally, and consequently effacing the tendency of the fluid to form vertical currents. Had the eyelids opened vertically, the vertical ridges would have been increased, and vision greatly impaired.

When every thing has been done to fit the *cornea* (the only part of the eye over which we have any direct command) for accurate vision, the general state of the health, or any casual irregularity of diet, will be sometimes found to affect the state of the organ, and unfit it for nice observation. To remedy this defect of vision, we must refer the patient to the simplest prescriptions of his physician.

When these precautions have been taken, the observer must protect his eye from all extraneous light; and the most effectual way of doing this is to use the snow spectacles of the Greenlanders, which are cut out of wood, so as to exclude all light whatever, except what enters through a circular aperture the size of the pupil, and directly in front of it.[1] A cast should be taken in plaster of Paris,

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[1] In the snow spectacles a long narrow slit is used, to enable the wearer to look on each side of him. An interesting account of the

from the part of the face to which they are to be applied, to enable the artist to cut them of a proper shape; and when finished they should be lined with black velvet.

The last requisite for accurate microscopical observation is steadiness in the microscope, and a steady and comfortable position for the observer. The first is easily attained. The second may be accomplished by the observer resting his doubled arms upon a stool or frame nearly the height of the eye-glass of the microscope, but unconnected with it, while his chin rests either upon his arms or upon his breast.

When all these means and precautions fail in unravelling a mysterious structure, we have often derived advantage, in the case of lined objects, by looking through cylindrical lenses or good prisms; the length of the cylinder, or the refracting edge of the prism, being at right angles to the lines. Narrow slits may also be used with advantage next the eye; but in all these cases, while we improve and give a finer definition to the lines and the spaces between them, we deteriorate vision for other parts of the structure.

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great value of these spectacles, by the celebrated Professor Blumenbach, will be found in the Edinburgh Phil. Journal, vol. viii. p. 261.

CHAPTER X.

ON TEST OR PROOF OBJECTS FOR TRYING THE PERFORMANCE OF MICROSCOPES.

This class of objects, and their application to the microscope, we owe to Dr Goring; and to their introduction we must ascribe much of the rapid improvement which this instrument has undergone. The finest test-objects are the scales of butterflies and moths, which were suggested to Dr Goring by the following passage in Leeuwenhoeck. "If we examine the wings of this creature (the silk-worm moth) by the microscope, we shall find them covered with an incredible number of feathers (scales), of such various forms, that if an hundred or more of them were to be seen lying together, each would appear of a different shape. To show more clearly this wonderful object, I caused eight feathers to be delineated, for I do not remember that I ever saw them of so curious a make in any flying insect.

"Although the microscope, by which these feathers

were drawn, represented objects very distinctly, *the limner could not through it see the ribs or streaks in each feather, until I pointed them out to him;* therefore, I put into his hands a microscope which magnified objects almost as much as that by which the silk worm's thread was drawn, desiring him to give the figure of that feather which through it he could see the most distinct."[1]

From this passage, Dr Goring naturally inferred, that there were some peculiar properties in the lines on the feathers and scales of insects, which rendered them more difficult to be discovered than other microscopic objects; and hence he discovered their properties as *test* or proof objects for trying the penetrating powers of microscopes. Mr Pritchard regards the *penetrating* power of a microscope as dependent on its angle of aperture, and its *defining* power as in the inverse ratio of the quantity of chromatic and spherical aberration. When the angle of aperture was less than a certain quantity, he found that the lined structure of the scales could not be rendered visible, however perfect the instrument was. The following is his list of test-objects, arranged in relation to *penetrating* and *defining* power. Several of these are represented in Plates XII. and XIII.

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[1] Select Works, p. 63.

I.—*Penetrating Power.*

Sect. I. *Easy.* 1. Petrobius maritimus, scales of, fig. 1.
2. Lepisma saccharina, scales of.

Sect. II. *Standard.* 1. Morpho Menelaus, feathers of, fig. 2.
2. Alacita pentadactyla, feathers of the.
3. Alacita hexadactyla, feathers from the body of it.
4. Lycænæ Argus, feathers of the.
5. Tenea vestianella, or clothes moth, feathers from under ends of the wing, fig. 3.

Sect. III. *Difficult.* 1. Pieris or Pontia brassica, or cabbage butterfly, feathers from the, fig. 4, 4*a*, 4*c*.
2. Podura plumbea, scales from the, fig. 5, 6, 7, 8, 9, 10, 11.

II.—*Defining Power.*

1. Hair of the common mouse, fig. 12–15.
2. Hair of the bat genus, fig. 16, 17.
3. Leaf of the moss *Hypnum*, species unknown.
4. Spotted scales of the *Lycænæ* Argus, fig. 24.

Besides these test-objects, which are copied from Mr Pritchard's drawings in the Microscopic Cabinet, we have added from the same source the following interesting objects:

1. A hair from the larva of the common Dermestes, fig. 18.
2. A white hair from a young cat, fig. 19.
3. The hair of a Siberian fox, fig. 20.
4. The hair of a common caterpillar, fig. 21.
5. A scale from the under side of the wing of the blue butterfly, the Lycænæ Argus, fig. 22.

In some of the preceding figures of the lined proof-objects the reader will perceive diagonal or oblique lines, as in fig. 9, 10, different from the longitudinal ones seen in fig. 1, 2, 3, 4, &c. These lines are reckoned more difficult to be seen than the longitudinal ones; and Dr Goring has mentioned those on the scales of the white-cabbage butterfly as a difficult test-object. Mr Potter, who has seen these diagonal lines, mentions also his having observed them on the scales of the wing of the small house-moth. As the nature of these oblique lines is far from being understood, and as their real existence is in our opinion questionable, we shall lay before our readers Mr Pritchard's observations on those observed in the scales of the *Podura plumbea* and *Pieris brassica*.

" In the foregoing account," says he, " of the different

scales from the wings and bodies of insects, the design has been to give their *appearances* under microscopes or engiscopes, without in the least determining their actual structure. When it is considered that these lines are less than the twenty thousandth of an inch distant, it must be allowed there is some difficulty in accurately determining their construction. The Morpho Menelaus and Lepisma saccharina are of sufficient size to distinctly perceive they are composed of two delicate tissues with longitudinal cords (probably tabular) disposed between them; but in the two delicate ones, the subject of these remarks, we perceive other systems of lines disposed obliquely; and as they are extremely delicate, it becomes a question whether they actually exist, or whether they are appearances produced under certain modifications of the illumination. As there is only one set shown at a time, and I have never been able to see them in the decided way of the longitudinal lines, I have been induced to consider them as appearances only, and not real lines. To determine this point, it became necessary to ascertain the cause that would produce such an effect; and it immediately occurred to me that these oblique lines were occasioned by the disposition and pressure of the superambient scales, in the same manner as the watering or wavy appearance communicated to corded silks and moreens by the pressure of

two pieces passed between rollers.[1] In examining the scales of the *Pieris brassica* under a deep power and large angle of aperture, I found them broad in some parts and almost invisible in others; and the same appearance presented itself in the curved lines on the scale of the *Podura plumbea*, some idea of which may be obtained by examining figs. 9 and 10 of Plate XII.

"The motive that has induced me to offer the above remark is, that it may lead to a complete investigation of the subject. What is here given is merely the crude idea that presented itself in the course of their examination as proof-objects."[2]

Dr Goring has published, in the Journal of the Royal Institution, vol. xxii. and also in the *Micrographia*,[3] many interesting observations on lined objects, of which it is necessary to give some account. In order to explain the effects of aperture on lined objects, he has represented in the *seven* circles shown in fig. 23, Plate XIII. the different appearances of a portion of the scale of the *Morpho menelaus*, shown in fig. 1, Plate XII. produced by increasing

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[1] I have since examined the *Petrolius maritimus* as an opaque object, which confirms this view of the nature of the oblique lines on its scales.

[2] Microscopic Cabinet, p. 160, 161. [3] Hall, 159, &c.

the aperture. He used a triple achromatic object-glass nine tenths of an inch focus, and half an inch in aperture, with a negative eye-piece of one fourth of an inch.

No. 1. shows the appearance of the scale when the aperture was one tenth of an inch, not a vestige of lines being visible.

No. 2. Aperture three twentieths; Dr Goring fancied he saw indications of lines or scratches.

No. 3. Aperture one fifth; traces of irregular scratches seen.

No. 4. Aperture three tenths; nascent lines recognised by a practised eye, like an aggregation of dots, but interrupted and broken.

No. 5. Aperture four tenths; the lines resolved, but not fairly. They are very faint, and seem ragged, as if still composed of dots and points.

No. 6. Aperture five tenths; the full aperture of the lens. The lines appear in their true character, as if drawn by a pen with some blue pigment on light violet-coloured paper.

No. 7. Same aperture. When the object is turned one fourth round, the cross striæ become perceptible.

Our limits will not permit us to give Dr Goring's excellent observations on the lines of the *Pontia brassica*, as seen also with apertures of different sizes in a reflecting microscope. With a well-figured metal, three tenths of an inch focus, and an angle of $55\frac{1}{2}°$ aperture, the lines and

cross striæ he found never to be resolved into dots and points, but to appear in what he supposes to be their proper character. "The two sets of diagonal lines," he remarks, "will be shown with a force and effect which will leave no doubt of their existence in the mind of a candid observer; the various lines, the longitudinal, the cross striæ, and the two sets of diagonals, being all observable *successively* by a slight change of illumination, though we can scarcely see two of the systems well at the same instant."[1]

Dr Goring elsewhere observes,[2] that the reflecting microscope invariably shows the diagonal lines on the *brassica* as distinct as the eye sees the ruled lines on a copy-book; that, in some "pet scales," one of the systems of oblique lines may be seen by looking into the instrument *directly*, and the other by looking into it *obliquely, without any alteration in the illumination;*[3] and that if one instrument shows the lines dotty, broken, interrupted, or ragged, while another shows them clearly made out as veritable lines or stripes drawn with a pen and ink, the latter is the best.[4]

Notwithstanding these repeated decisions of Dr Goring, he seems, in an earlier part of his volume,[5] to have had some misgivings on the subject. In speaking of the lined tests, he says, "*There is an inexplicable mystery about them,*

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[1] *Micrographia*, p. 163. [2] *Micrographia*, p. 130 and 144.
[3] Ibid. p. 102, note. [4] Ibid. p. 104. [5] Ibid. p. 44.

for if their lines are in reality produced on the same principle as those of micrometers, why are they not as easily seen? No penetrating power or large angular aperture is requisite to bring out the lines on a micrometer, though divided nearly as finely as ordinary tests, to the extent perhaps of 10,000 in an inch." These observations are just and philosophical, and we would add only a single observation in support of them, that Dr Wollaston made platina wires the 18,000th of an inch in diameter, and saw them distinctly; and we venture to say, that in no instrument whatever would such lines appear either dotted or ragged.

Such was the state of this subject when these lined objects were examined by Sir David Brewster, both in reference to their action upon light when observed by the naked eye, and when placed under the microscope as test-objects. Having been occupied for several years in a series of analogous observations on the lines which apparently separate the component fibres of the crystalline lenses of animals, he was familiar with the class of optical illusions which interfere with the accurate development of such structures.

Upon exposing the finest lined objects to a bright light, and excluding as much as possible all other extraneous rays, he saw distinctly the fringes of colour produced by interference; and on measuring the angular distances of the first red fringe from the light, he found that the distance

of the lines, or rather the diameter of one black line and half the bright space between the lines, varied from the 10,000th to the 22,000th of an inch. Hence, if we take the black lines and their intervals to be equal, the diameter of each will vary from about the 13,000th to the 29,000th of an inch.

Although these apparent lines give colours by interference, exactly like the analogous lines in the laminæ of the crystalline lens, yet neither of them are *real lines*, as decided upon by Dr Goring. With small apertures the lines in the crystalline lens appear *dotty*, *interrupted*, *uneven*, and *ragged*, and exhibit, in short, all the general phenomena of the lines on proof-objects; but with a good microscope and a large aperture, we discover the true secret of all these appearances. They are not lines, but a succession of teeth arranged in lines; and from the great number of lines forming the sides of the teeth, they appear dark. Each fibre, in short, has teeth on each side of it,[1] and the teeth of one fibre lock into the spaces between the teeth of the adjacent fibres. When we trace these fibres towards the pole to which they converge, they become smaller and smaller, the teeth diminishing in the same proportion, so that they become as difficult, and finally more difficult, to resolve, than the lines in the proof-objects.

[1] See Phil. Trans. 1830.

After a laborious examination of the lined tests, and the use of every optical resource which he could command, Sir David Brewster has found that the mysterious lines on these test-objects are only apparent lines, being composed of a succession of interlocking teeth, by which the fibres to which they are attached form that delicate film which composes the scale of a moth. We now see the source of all the perplexities which have beset this class of observations. We understand why such lines are not seen so distinctly as the real lines on micrometers, and the dots and the raggedness are all explained. In the lenses of quadrupeds the teeth of the fibres are not round like those of fishes, but are often sharp-pointed and extremely short, like a jagged line, or a line with points projecting from it. In like manner, the separation of the teeth is much more distinct in some of the lined objects than in others. See fig. 24, in which we have given a rude representation of the lines.

With regard to the diagonal or oblique lines, which have been such a source of perplexity to microscopical observers, we have little hesitation in pronouncing *those which we have seen* to be optical illusions, from the accidental *alignement* of the sides of the teeth in different grooves, when similarly illuminated by oblique rays. When the scales are immersed in diluted sulphuric acid, we have never seen the diagonal lines. When the sulphuric acid

is too strong, the scales curl up, and often in this state exhibit the lines very beautifully. We have observed diagonal lines singularly developed in the laminæ of the crystalline, and clearly arising from the interference of the rays acted upon by the lines on one side of the lamina, with the rays acted upon by the lines on the other side, and therefore we have been the more confirmed in our opinion. As we have not had the advantage, however, of using any of the fine reflecting microscopes with which Dr Goring observed the oblique lines so distinctly brought out, it is still with considerable diffidence that we place our conclusions in opposition to so direct and distinct an observation, made by such skilful and experienced observers as he and Mr Pritchard.[1]

With the view of arriving at a just decision respecting the nature of the lines, Sir David Brewster endeavoured to

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[1] Mr Pritchard informs us that the diagonal lines or cross striæ are most easily seen in the scales from the wing of the *Euplœa limniacæ*, and in the blue scales from the *Papilio Paris*, where they "are strongly and easily developed under a power of from 100 to 200 times." In speaking of the ordinary lines, Mr Pritchard remarks, that these lines or "markings," with his best instruments, "appear detached like short hairs or spines covering the delicate tissue of the scale. This latter appearance is correct, the prominent portions of the lines which have escaped the pressure of those of the surrounding scales being in a plane above the other por-

ascertain the disposition of the colouring matter on the scales. Owing to the great brightness of the lines on the black scales, especially near their root, he was at first disposed to infer that, at least in these scales, the colouring matter was arranged along the black lines, the particles being more readily detained in their places by the edges of the teeth. He has found, however, that in other scales the colouring matter lies also along the bright lines; and it is only when this colouring matter is removed, or its effect masqued, by removing the refraction at its surface by immersion in a fluid, that the lines of proof-objects are developed with perfect distinctness.

Sir David Brewster has made an attempt to count the number of scales and teeth in the wing of a brown moth, or in one superficial inch, the area of the two surfaces of each wing. He supposes, of course, all the scales to be the same in size and structure, and he finds that there are

Scales	158,400
Teeth	19,800,000,000

or nineteen thousand eight hundred million.

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tions of the lines." This opinion of the structure of the lines, published in 1835, is not repeated in the *Micrographia*, published in 1837, where Dr Goring decides that they are real lines. See *List of* 2000 *Microscopic Objects*, p. 10. Lond. 1835.

CHAPTER XI.

ON MICROSCOPIC OBJECTS.

In the preceding chapter we have already described some of the most interesting objects for microscopical observation. Every department of nature is full of objects, from the examination of which the most important discoveries may be expected; but though the zealous observer can never be at any loss for subjects of research, it is desirable to know what has been done by our predecessors, and what trains of inquiry are most likely to prove of general interest. There are subjects of microscopic inquiry which are closely connected with the most interesting parts of physiology; and even geology itself, conversant with the grandest subjects of research, has recently been illustrated by the aid of the microscope.

Dr Ehrenberg of Berlin, to whom we are indebted for so many important discoveries respecting the organization of

infusorial animalcules,[1] has lately made the most remarkable discovery of *infusorial organic remains.* These remains are the siliceous shells of animalçules belonging to the division Bacillaria, and form strata of Tripoli, or poli-schiefer (polishing-slate), at Franzenbad, in Bohemia.[2] M. Ehrenberg has still more recently discovered them in the semi-opal found along with the polishing-slate in the tertiary strata of Bilin, in the chalk flints, and even in the semi-opal or noble opal, of the porphyritic rocks.[3] The size of a single individual of these animals is about $\frac{1}{288}$th of a line, or $\frac{1}{3456}$th of an inch. In the polishing-slate from Bilin, in which there appear to be no vacuities, *a cubic line* contains, in round numbers, 23 millions of these animals, and *a cubic inch* contains 41,000 millions of them!

The weight of a cubic inch of the polishing-slate is 270 grains. There are, therefore, 187 millions of these animals in a single grain, or the siliceous coat of one of these animals weighs the 187 millionth part of a grain!

In Plate XIII. figs. 24 and 25, we have given representations of these singular microscopic objects, as seen by Ehrenberg. The siliceous shells found in the Franzenbad

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[1] *Organization Systematick der Infusions Thierchen*, 3 vols. folio, Berlin, 1830–1834.

[2] Poggendorff's *Annalen der Physik*, 1836, No. V. p. 225.

[3] *Ibid.* No. VI. p. 464.

poli-schiefer are much more distinct than those found in the Bilin strata. Among the former we discovered a microscopic shell of a quite different kind, whose length was equal to half that of the shells shown in fig. 24, and in which there were lines or grooves exactly resembling those in the scales of moths.

Another example of the value of microscopical observations may be drawn from the discovery of the teeth of the fibres which compose the crystalline lenses of almost all animals. The crystalline lens is composed of innumerable fibres of nearly the same length, each of which tapers from its middle to its two extremities, where it comes to the sharpest point. The sides of each of these fibres are furnished with teeth like those of a watch-wheel, and the teeth of the one lock into those of the adjacent ones, as shown in fig. 28, Plate XIV. When the power is small, or the microscope not good, or the laminæ too thick and not nicely detached, each row of interlocking teeth appears as a dark line, sometimes as sharp as a black line drawn upon paper with a pen. Sometimes the lines appear rough and ragged, and as the fibres become less and less in approaching the poles, the black lines are as difficult to resolve into teeth as the lines on test-objects already described. The following measures, taken by Sir David Brewster, will show what a wonderful structure in the eye has been thus disclosed to us by the microscope.

The calculations refer to the lens of a cod, four tenths of an inch in diameter.

Number of fibres in each lamina or spherical coat....2,500
Number of teeth in each fibre..........................12,500
Number of teeth in each spherical coat.........31,250,000
Number of fibres in the whole lens................5,000,000
Number of teeth in the lens..................62,500,000,000

or the lens of a cod contains five millions of fibres, and sixty-two thousand five hundred millions of teeth; and if we reckon the curved end of the tooth as one surface, each tooth will have six surfaces,[1] which come into contact with the corresponding surfaces of the adjacent tooth, so that the number of touching surfaces will be *three hundred and seventy-five thousand millions*;[2] "and yet this little sphere of tender jelly is as transparent as a drop of the purest water, and allows a beam of light to pass across these almost innumerable joints without obstructing or reflecting a single ray!"

There is another class of objects of extreme interest, which Mr Pritchard has omitted to notice, and the development of which called forth all the resources of optical knowledge and practical experience with the microscope. These objects are the microscopic cavities in mine-

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[1] This includes the concave surface between two adjacent teeth.

[2] Philosophical Transactions, 1833, p. 329.

rals, containing two fluids unknown to the chemist, groups of crystals, floating balls, and exhibiting actual chemical operations going on in these minute laboratories when exposed to changes of temperature. These various phenomena have been described and represented in drawings, in two papers by Sir David Brewster, published in the Transactions of the Royal Society of Edinburgh. In some of the precious stones, particularly in diamond, garnet, &c. these cavities are perfect spheres ; but, owing to the great refractive power of the gem, they appear completely black and opaque, though the microscope descries a small spot of light in their centre, which is the pencil of light which they refract. These spherical cavities, and this central spot, are the finest objects for examining the aberration of lenses and specula, and are infinitely preferable to the reflected patches of light from small spherules of quicksilver. Dr Goring has observed spherical cavities or air-bubbles in fluids, and, with his usual ingenuity, recognised their utility for indicating the effects of aberration. Those which we have used in the gems are, however, permanent instruments of much greater utility, not only from our being able to use the same bright spot with all instruments and on all occasions, but from the dark ring round the bright spot being incomparably greater in the gems than in fluids.[1]

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[1] The ratio between the diameter of the dark sphere and of the

Representations of some of the cavities in fluids are given in Plate XIV. fig. 29, 30, 31. Fig. 29 shows the cavities containing the two new fluids, which will not mix, though in the same cavity. The little circle is the bubble either of gas or of vacuity. The fluid round it is a highly evaporable fluid, and the fluid in the angles and ends of long cavities is a thick and unevaporable fluid, which indurates when exposed to the air. Figs. 29 and 30 are beautifully formed cavities in topaz.

Our limits will not permit us to pursue this subject farther, and we shall conclude the article with a very brief selection of microscopic objects from Mr Pritchard's admirable little pamphlet, entitled a List of 2000 Microscopic Objects.

1. Insects,—Eggs, wings, tongues, antennæ, and scales of.

Eyes of, Agrion, 12,000 eyes; Bombyx mer, 6236 eyes; Phalæna cossus, 11,300; Scarabæus, 3180; Hawk-moth, 20,000; Libellula, 12,544; Melalontha, 8820; Mordella, 25,088; Papilio, 17,000.

2. Hairs of Animals. Hair of an infant, Ornithorynchus, mouse, bat, bee, Acilius canaliculatus, Melecta

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small luminous spot gives a measure of the refractive power of the solid or fluid.

punctatus, Siberian fox, spider, wing of Tipalis, stag-beetle, white cat, dormouse, dermestes, caterpillar, badger, ant-eater, civet cat.

3. Scales of Insects. Podura plumbea, Pontia brassica, Pieris brassica, Parnassus Apollo, Atlas moth, diamond-beetle, Euplœa limniacæ, house-moth, Lepisma saccharina, 10-plumed moth, 20-plumed moth, Morpho Menelaus, Papilio Apollo, Papilio Paris, Urania leilus, privet moth.

4. Circulation in Plants, or *Cyclosis.* Nitella hyalina, Nitella translucens, Chara vulgaris, Caulinia frigalis, Hydrocharis or frog-bit in the stipulæ of the leaves and the ends of the roots, Tradescantia virginica or spiderwort in the filaments around the stamina, Senecio vulgaris or groundsel in the hairs surrounding the stalks and flowers.

5. Circulation in Animals. In the arachnoida or spider tribe at the joints of the legs, Peria viridis and Semblis bilineata on the antennæ and wings when they have just emerged from the chrysalis, larva of the Ephemera, larva of Hydrophilus, small Dysticus, Agrion puella, Libellula, round Lynceus, fresh-water shrimp, water-hog (Oniscus), Ligia, water-flea (Daphnia pulex). (See Pritchard's Microscopic Illustrations, and Microscopic Cabinet.)

6. Circulation in Zoophytes. Mr Lister has discover-

ed a circulation resembling that in plants in some of the polypiferous zoophytes, as the Tubularia indivisa, Sertulariæ, Campanulariæ, Plumulariæ, &c.

7. Crystals. For an account of various interesting microscopic phenomena observed by H. F. Talbot, Esq. of Lacock Abbey, we must refer the reader to a series of interesting papers in the recent numbers of the London and Edinburgh Philosophical Magazine, and to others which will be found in the Philosophical Transactions.

The oxalate of chromium and potash dissolved in water and rapidly crystallized is a fine object. In polarised light the most splendid object is the Faro Apophyllite when the prisms are complete, as represented by Sir D. Brewster in a coloured drawing in the Edinburgh Transactions, vol. ix. p. 317, plate xxi. fig. 1.

Size.

8. Animalcules. Monas Termo, 18,000th of an inch.

Monas atomus, 4000th of an inch.

Monas volvox, 3456th to 1728th of an inch.

Volvox globator, found in stagnant water, 30th of an inch.

Vibrio bipunctatus, 200th of an inch.

Vibrio spirillum, like a screw, 2000th to 1000th of an inch.

Size.

Vibrio glutinis.[1]

Kolpoda cucullus, 28th of an inch.

Cercaria podura.

Cercaria viridis.

Cercaria hirta.

Leucophrys fluida, 400th of an inch.

Trichoda vulgaris, 1200th to 240th of an inch.

Trichoda longicauda.

Vorticella polymorpha.

Vorticella convallaria.

Vorticella senta, 100th of an inch.

Vorticella rotatoria.[2]

The reader will find beautiful drawings and full descriptions of these and many other animalcules in Mr Prit-

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[1] Figured by Dr Goring in the Microscopic Cabinet.

[2] The Rotifer vulgaris. See Microscopic Cabinet, chap. vi. p. 58–69; and Pritchard's Nat. Hist. of Animalcules, p. 167. The reader will find a very interesting discussion of the apparent rotatory movements of the wheels of this extraordinary animalcule, by Mr Faraday, in the Journal of the Royal Institution, vol. i. New Series, p. 220; October 1830, May 1831. See also Baker, Of Microscopes, vol. ii. p. 266–295; Adams on the Microscope, p. 548; and Leeuwenhoeck in the Phil. Trans. No, 283, 295, 337.

chard's interesting work entitled The Natural History of Animalcules, London, 1834; in the Microscopical Illustrations of Mr Pritchard and Dr Goring; and in the Microscopic Cabinet by the same authors he will find everything that he desires respecting microscopic objects.

Dr Ehrenberg, whose discoveries we have already referred to, has lately presented to the British Museum a series of dried microscopic objects, consisting chiefly of infusorial animalcules, globules of the blood of the sheep and frog, &c. along with a brief notice of his method of preparing them. "Dr Ehrenberg," says Mr Children, who has most judiciously published[1] an account of this valuable donation, "preserves these most minute and perishable of known organic forms by means of rapid desiccation on little plates of mica, in which manner he informs us that he has succeeded in making a very satisfactory dried collection, not only of nearly 300 species of *Infusoria*, but also of other kinds of microscopic objects. He mounts them between double plates of mica, fixed in the cells of slides, in the usual manner of preparing the scales of butterflies and *Podurœ*, and other transparent microscopic objects; and thus he says, 'I have not only preserved the form and colour of the *shielded cuirasses*, *Rotatoriœ* and *Bacillariœ*, but also the *softest* and *most delicate* of the polygastric

[1] Lond. and Edin. Phil. Mag. August 1836, vol. ix. p. 90.

Infusoria, even those of the genus *Monas;* as well as the tissue of plants; the *Spermatozoa* and *Cercariæ;* the different sorts of globules of blood, with their nuclei; globules of lymph, chyle, and milk; and the nervous tubes, &c. of a great number of animals, and of man."

A power of about 300 (linear) is sufficient for viewing these objects; "but a lower power does not show them satisfactorily, however well they may be illuminated."

We subjoin a list of the subjects presented to the museum by Dr Ehrenberg.

Slide No. 1.

1. Monas viridis.
2. Polysoma uvella, and Monas termo.
3. Spirillum undula, and Vibrio bacillus.
4. Euglenia acus, Eu. viridis, Eu. pyrum.
5. Coleps hirsutus.
6. Volvox globator.

No. 2.

1. Paramecium caudatum.
2. Glaucoma scintillans.
3. Trichoda carnium.
4. Carchesium polypinum.
5. Epistylis nutans.
6. Euplotes Charon.

No. 3.

1. Stentor niger.
2. Paramecium aurelia.
3. Glaucoma scintillans.
4. Stentor polymorphus.
5. Stentor cæruleus.
6. Idem, compressed to show testiculi.

No. 4.

1. Nassula ornata.

2. Nassula elegans.
3. Nassula aurea.
4. Idem, crushed to show the teeth.
5. Chilodon uncinatus.
6. Chlamydomonas pulvisculus.

No. 5.

1. Hydatina senta.
2. Idem, crushed to show the teeth.
3. Polyarthra trigla.
4. Brachionus pala, with its eggs.
5. Brachionus rubens, ditto.
6. Anuræa aculeata.

No. 6.

1. Globules of blood of the sheep (ovis aries).
2. Ditto of the frog (rana temporaria).
3. Grains of the retina of the eye of the same.
4. Spermatozoa vespertilionis murini.
5. Arhnanthes longipes.
6. Meridion vernale;
   Fragilaria rhabdosoma:
   Navicula acus;
   Na. Amphisbæna.

FINIS.

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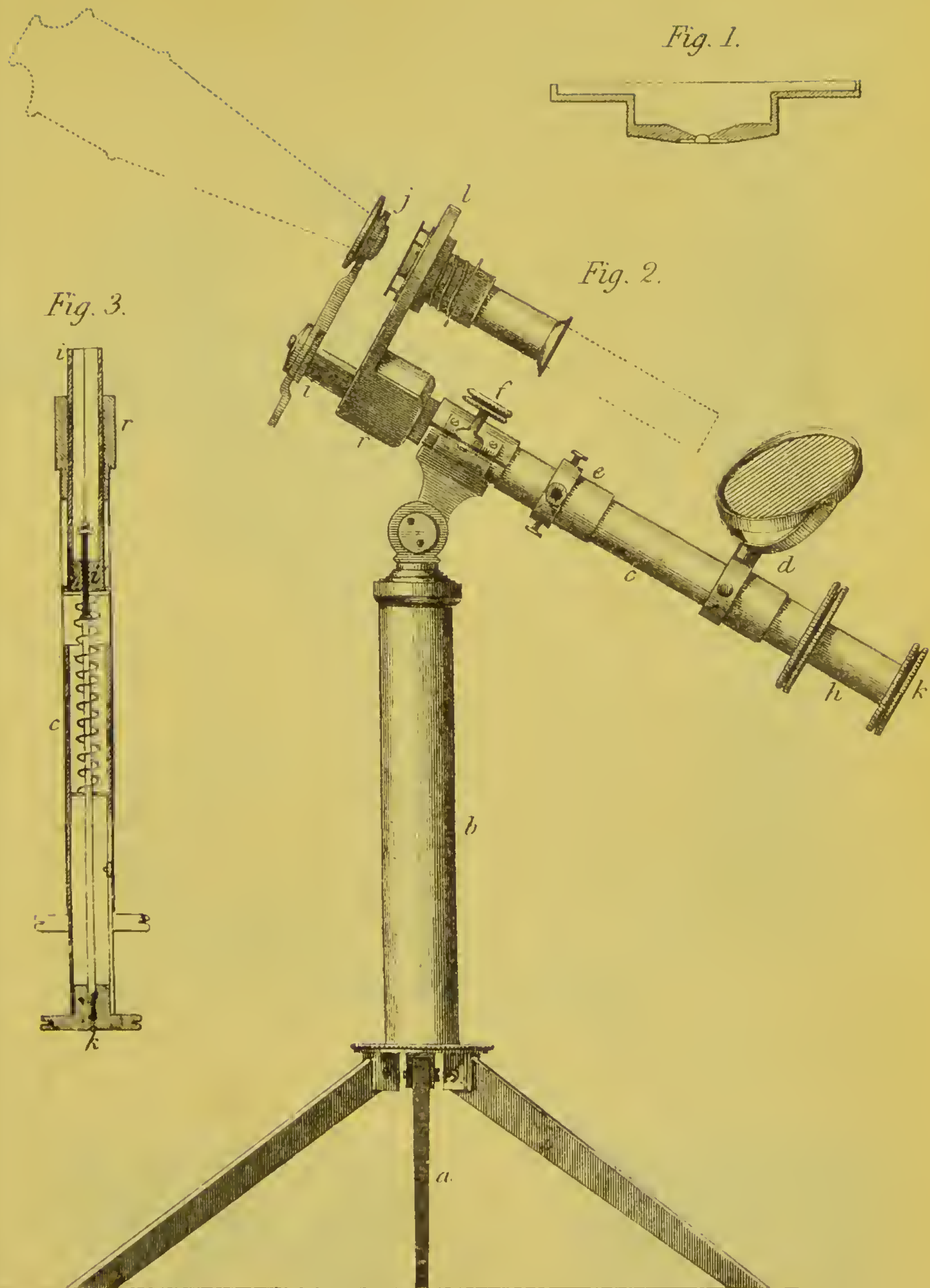
ERRATUM.

Page 124, line 1, for *all the micrometers above described*, read *all micrometers.*

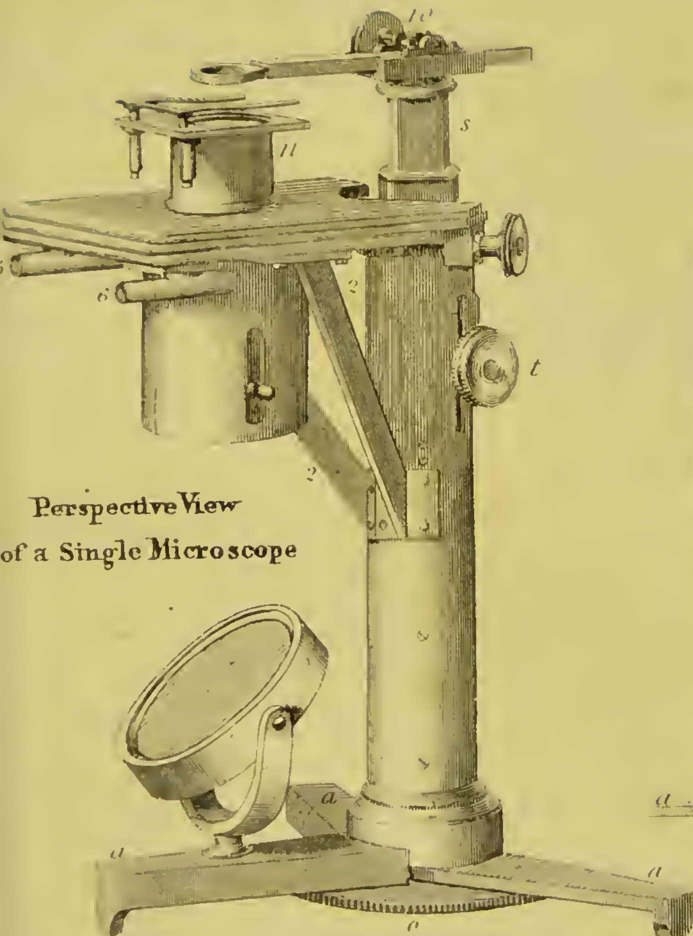
PLATE I.



A Single Microscope.

PLATE II.

Fig. 4



Perspective View of a Single Microscope

Fig. 5.

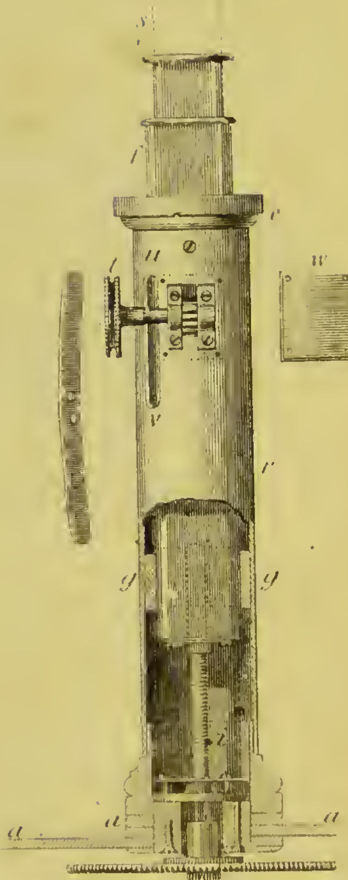


Fig. 6

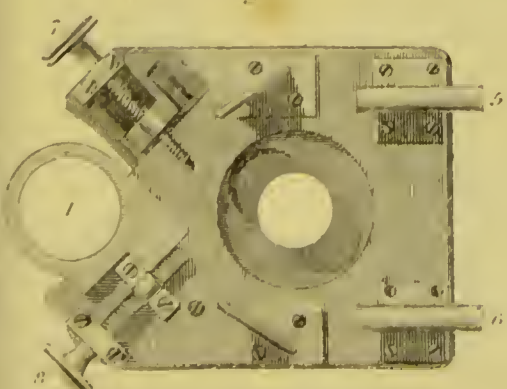
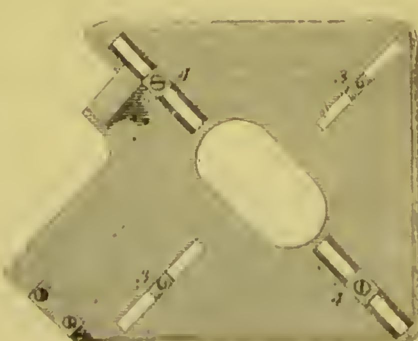


Fig. 7.



Nichol Edin.r

PLATE III.

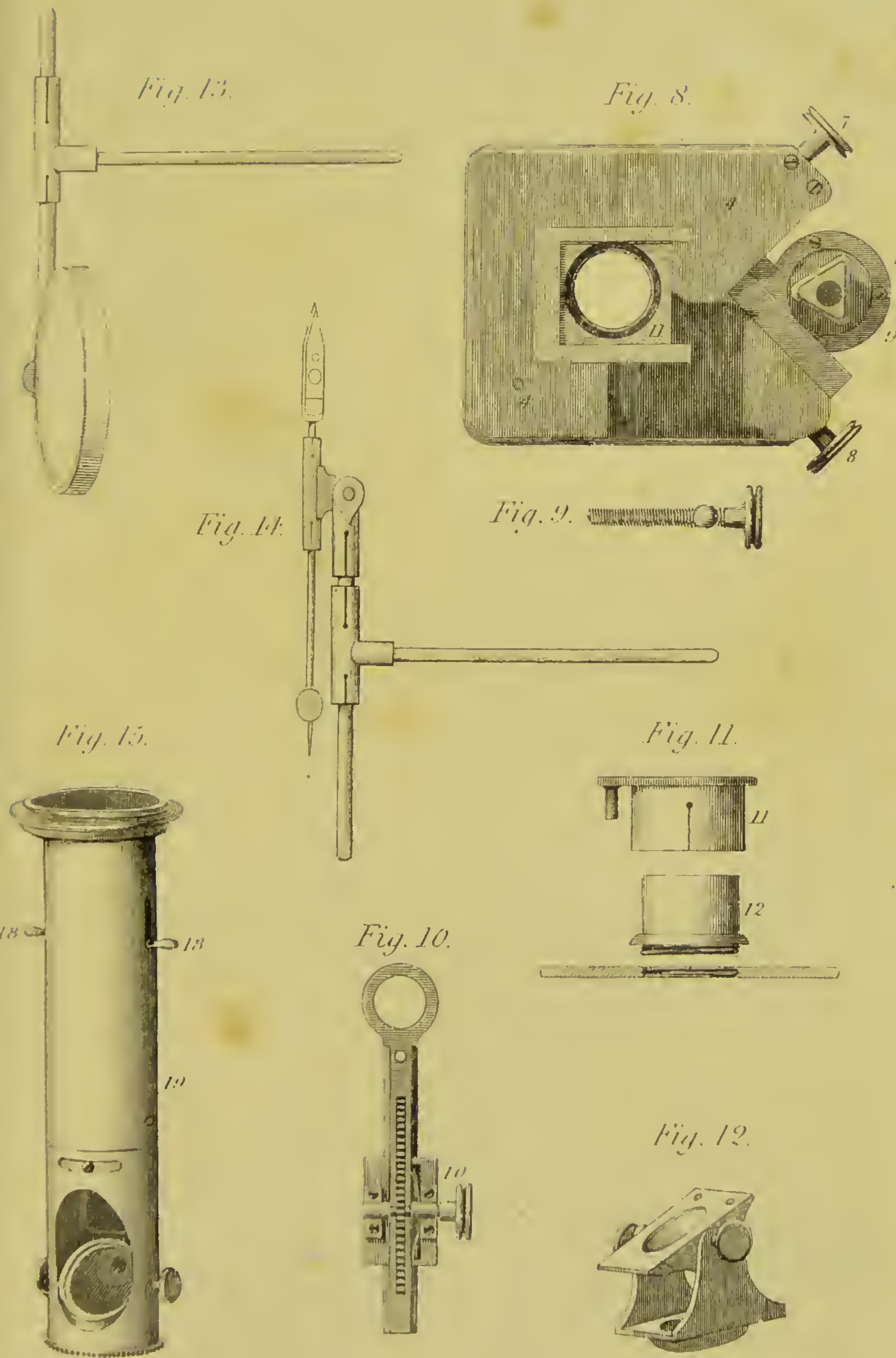


PLATE IV.

Fig. 16.

Fig. 17. 18.

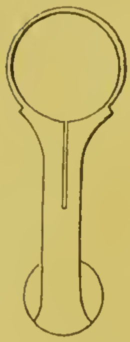


Fig. 20.

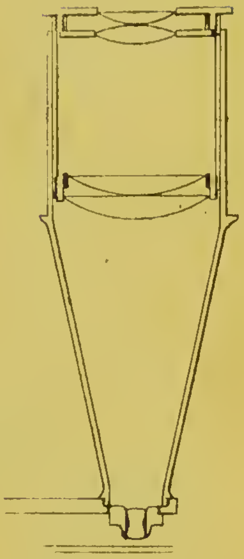


Fig. 19.

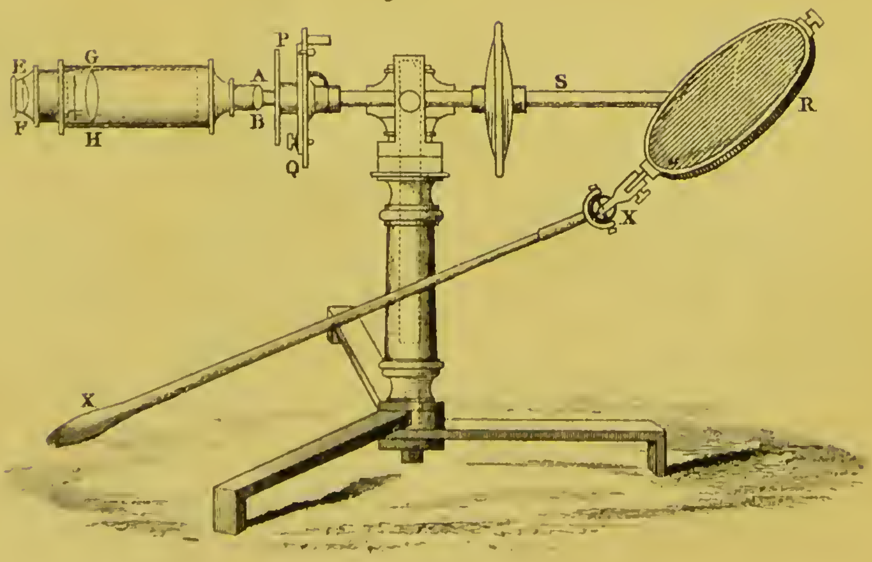


PLATE V.

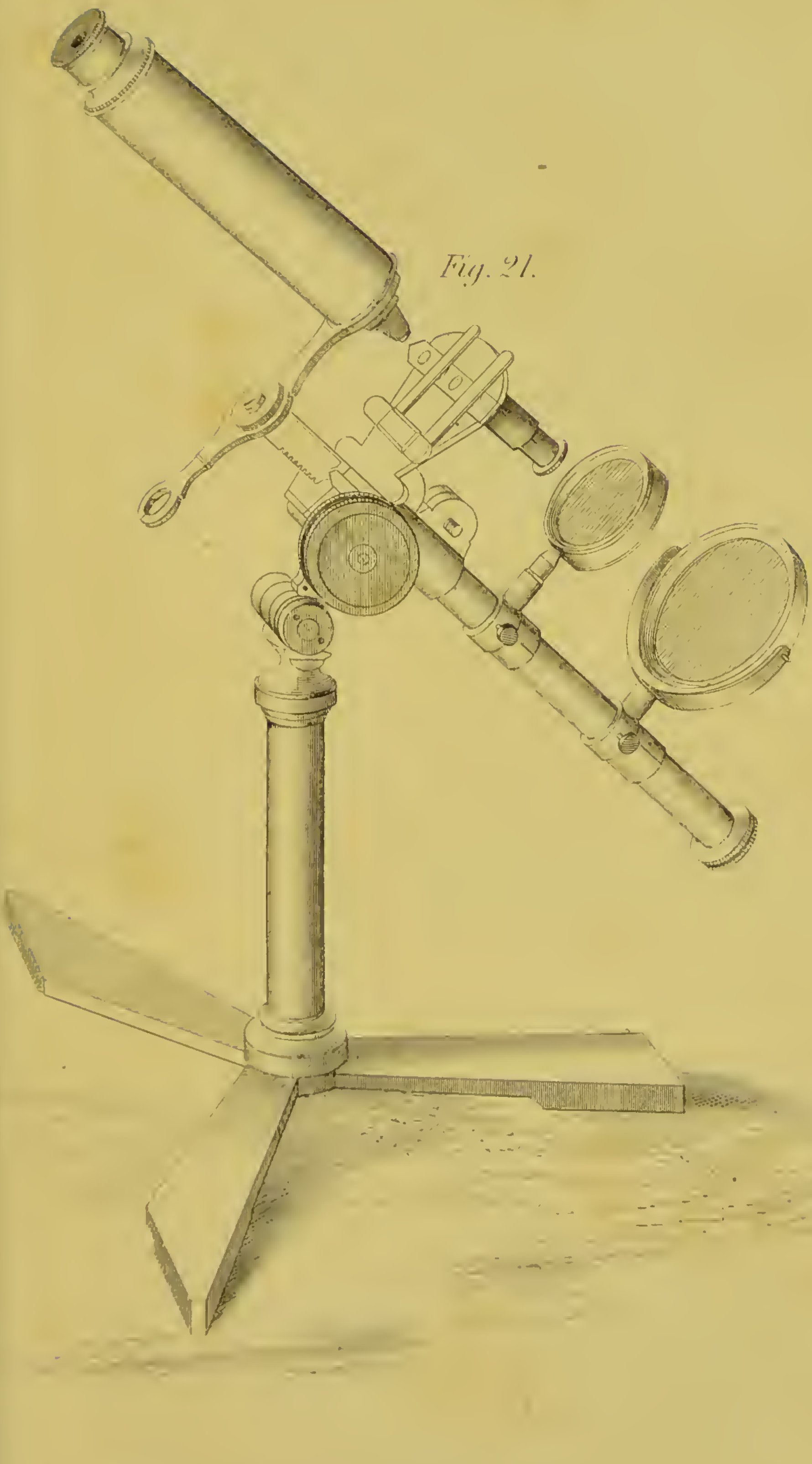


Fig. 21.

Pritchard's Compound Achromatic Microscope

Nichol Edin.

PLATE VI.

Pritchard's Compound Achromatic Microscope.

Fig. 22.

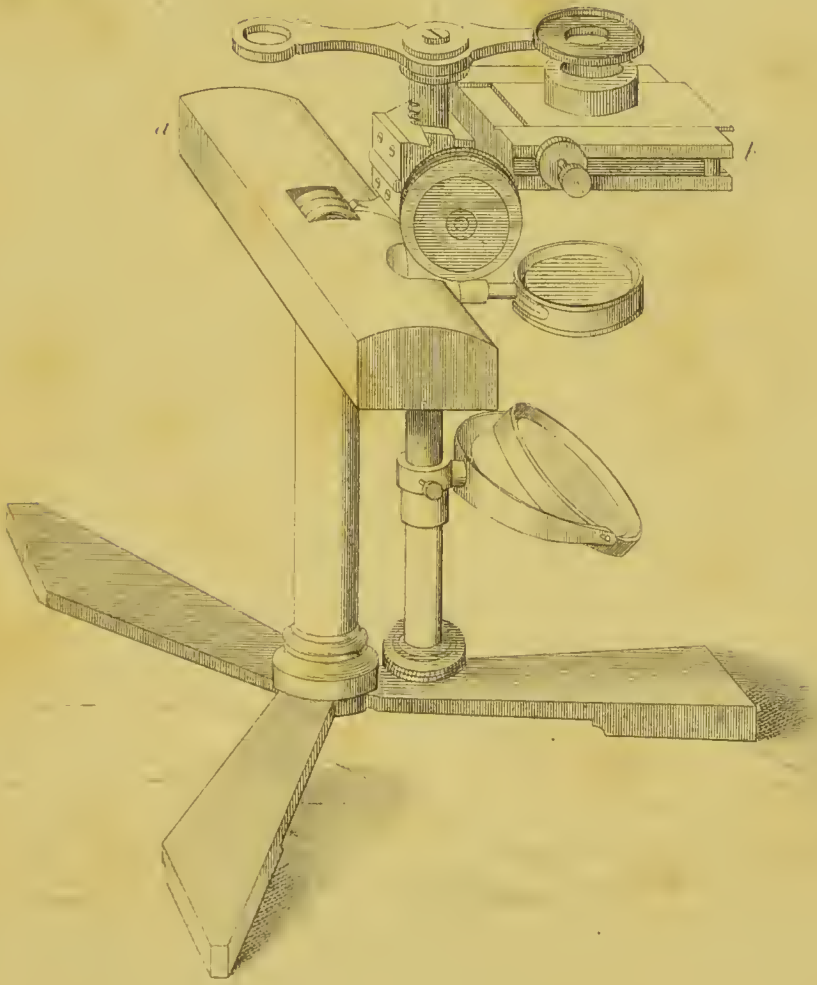


Fig. 24.

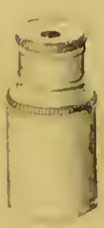


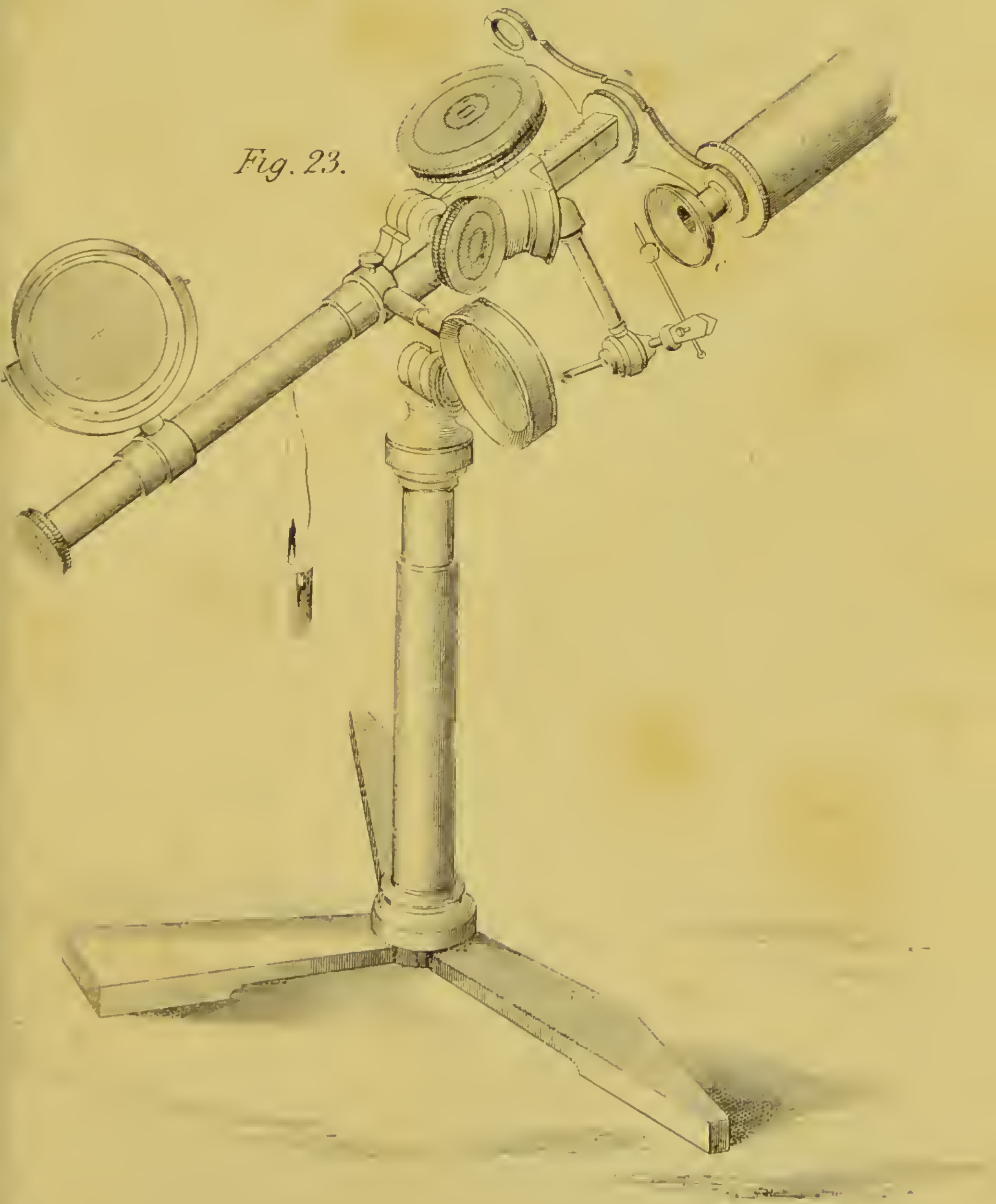
Fig. 25.

Nichol Edinr.

PLATE VII.

Pritchard's Improved Achromatic Microscope.

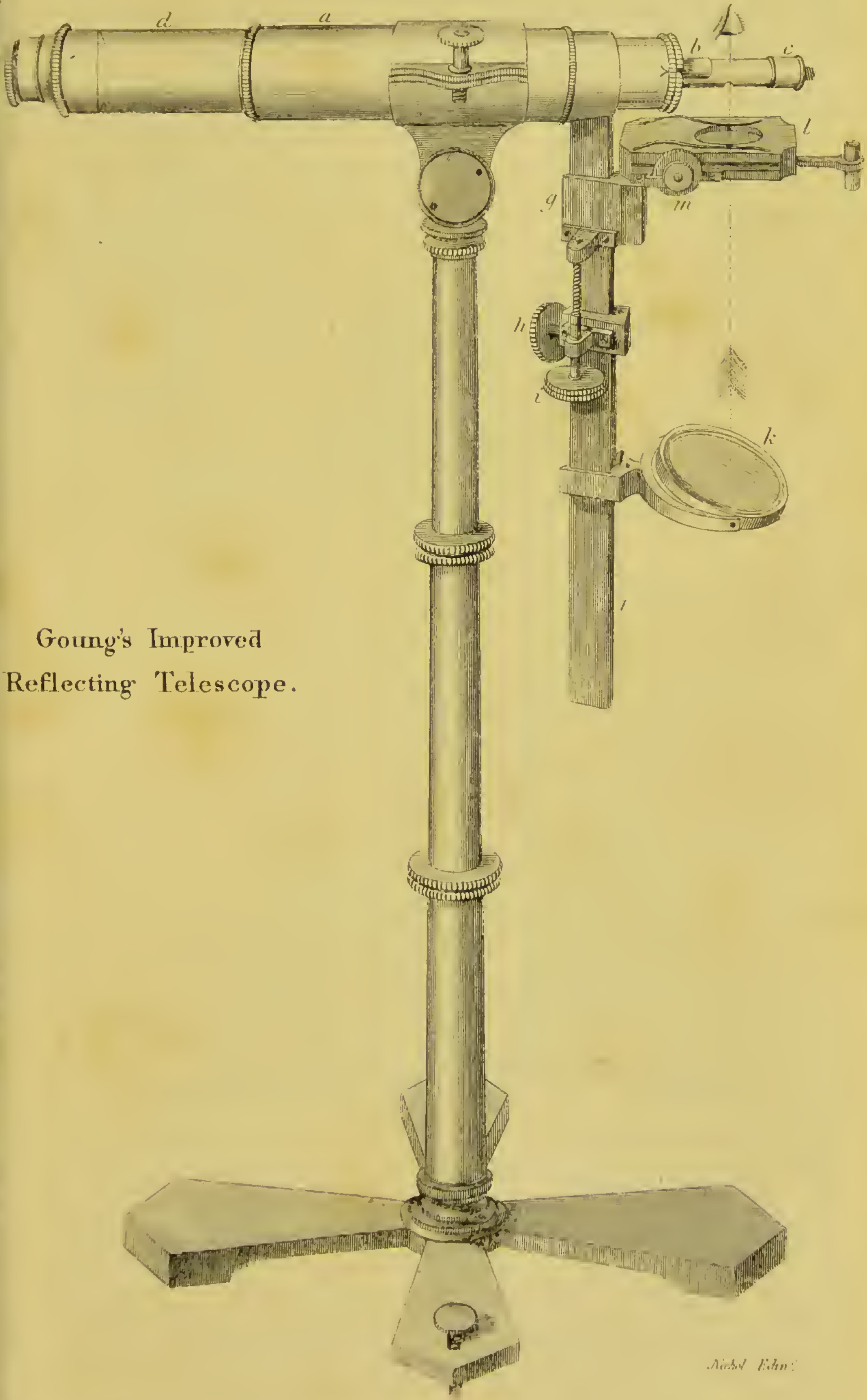
Fig. 23.



Nichol. Edinr

PLATE VIII.

Fig. 26



Goung's Improved
Reflecting Telescope.

PLATE IX.

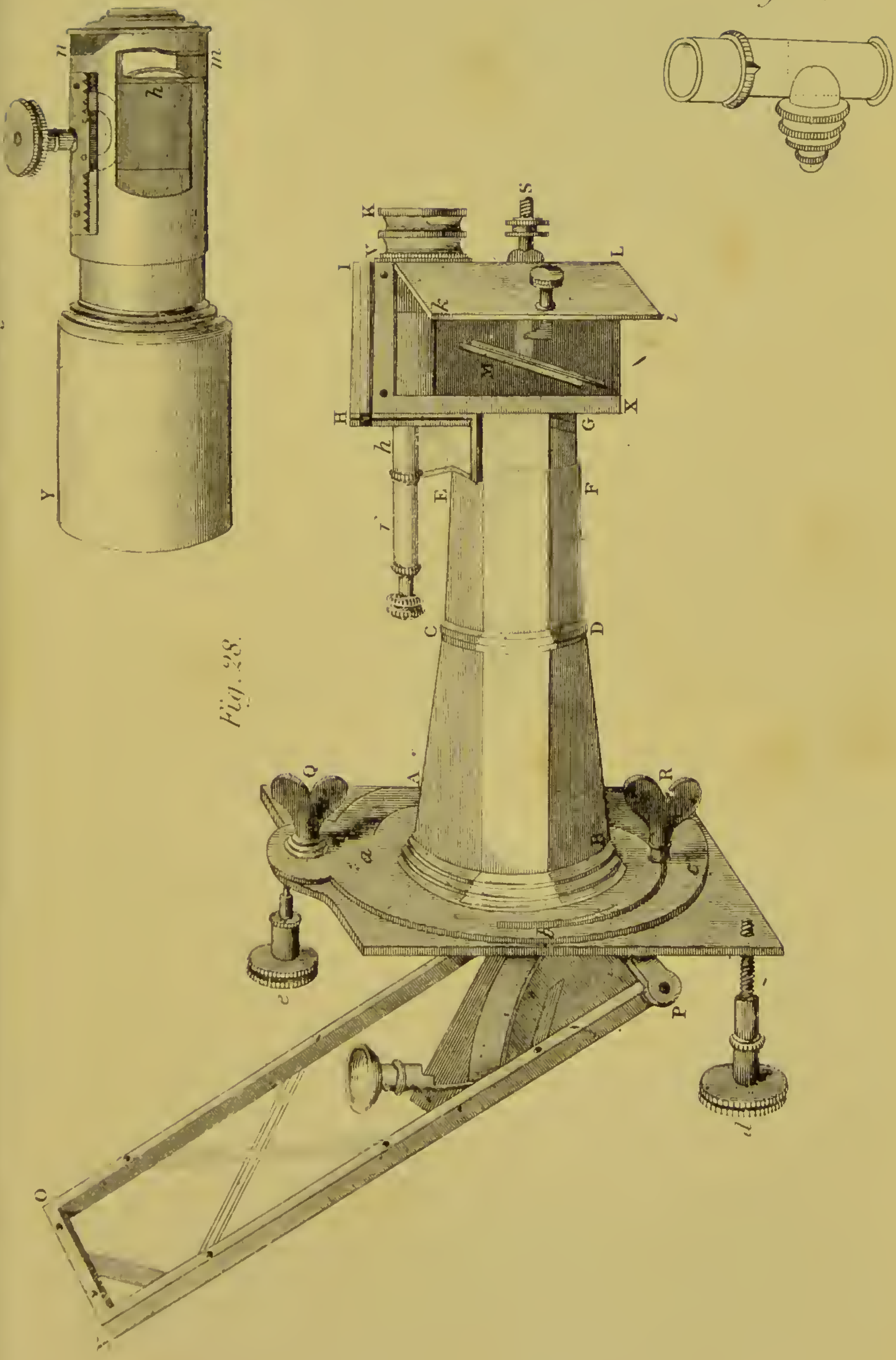


Fig. 27.

Fig. 28.

PLATE X

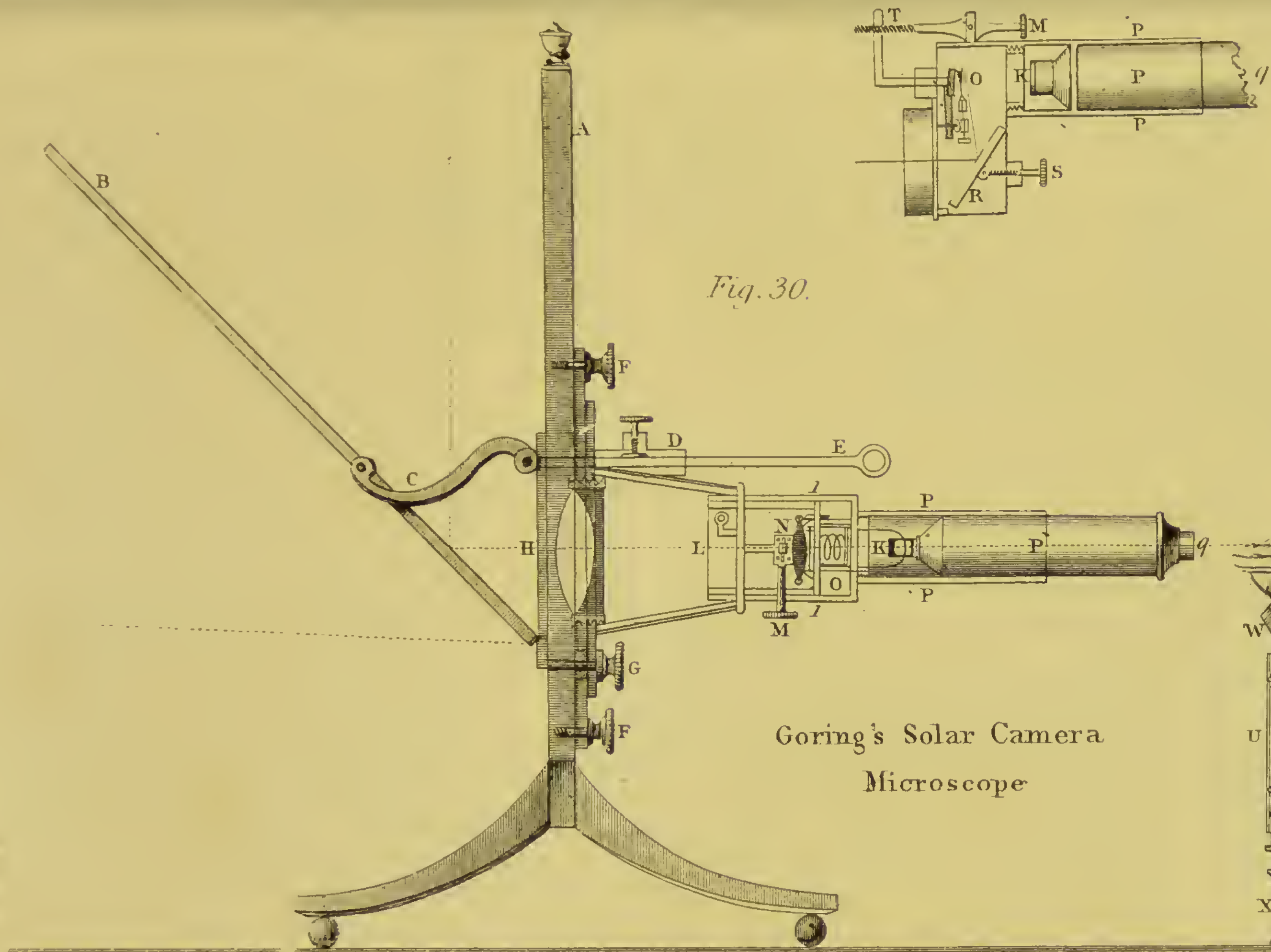


Fig. 30.

Fig. 33.

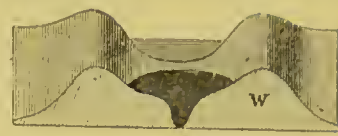
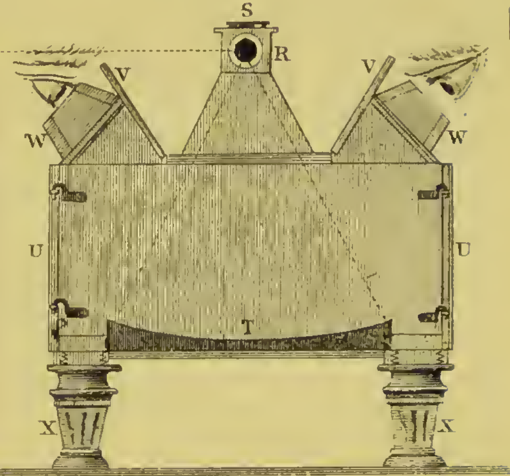


Fig. 31.



Goring's Solar Camera Microscope

PLATE XI

Fig. 33.

Fig. 34.

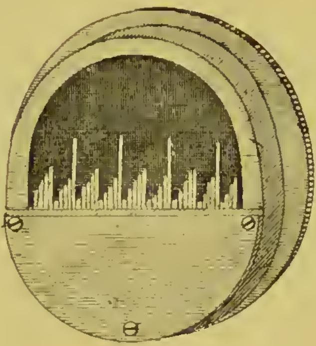


Fig. 35.

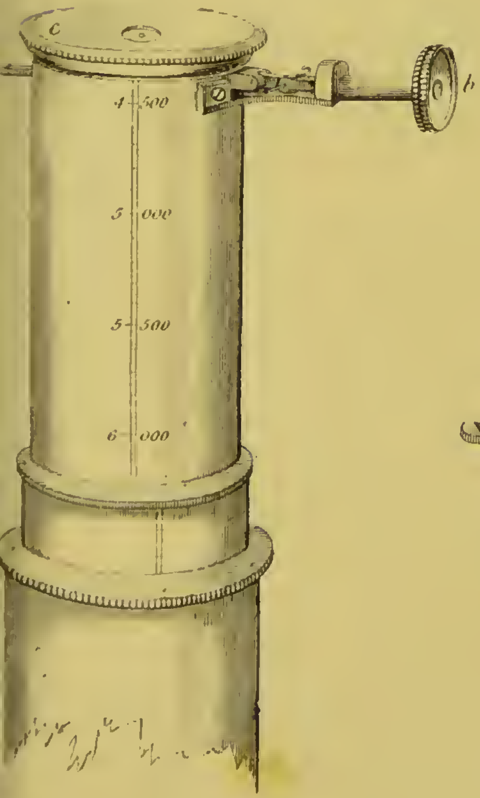
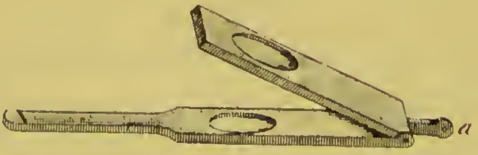


Fig. 36.



Dr. Wollaston's Micrometer.

PLATE XII.


Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.
Fig. 8.
Fig. 9.
Fig. 10.
Fig. 11.
Fig. 12.
Fig. 13.
Fig. 14.
Fig. 15.
Fig 16
Fig. 17.
Fig. 18.
Fig. 19.
Fig. 20.
Fig. 21.
Fig. 22.

PLATE XIII.

Microscopic Objects.

Fig. 23.

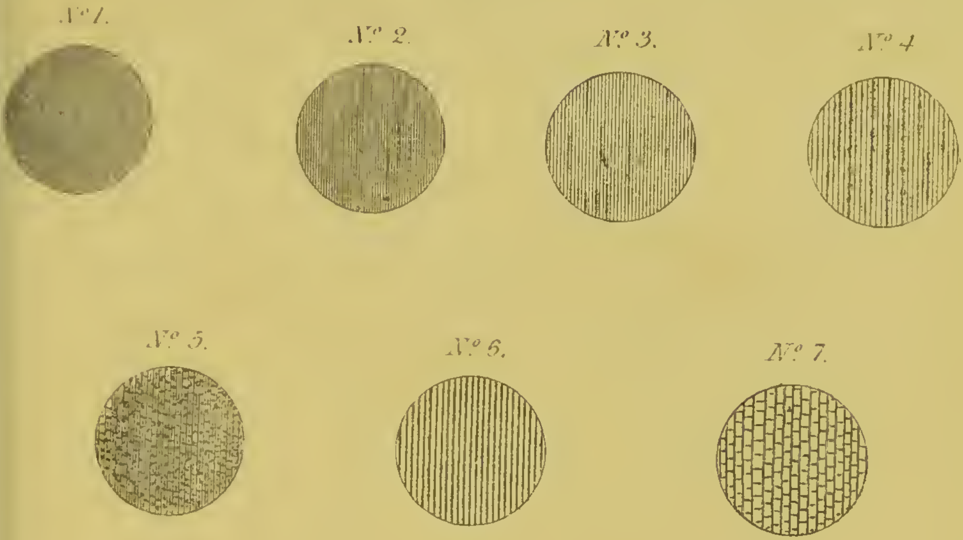


Fig. 24.

Fig. 25.

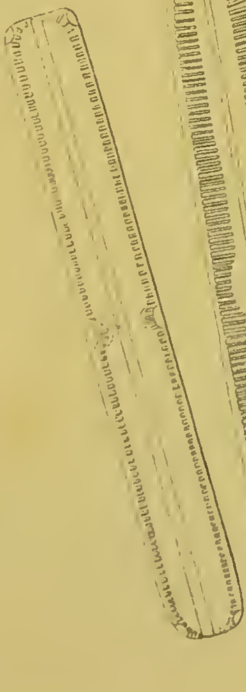


Fig. 26.

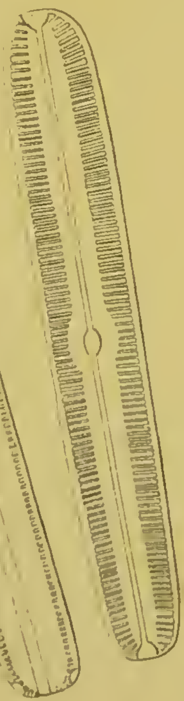


Fig. 27.

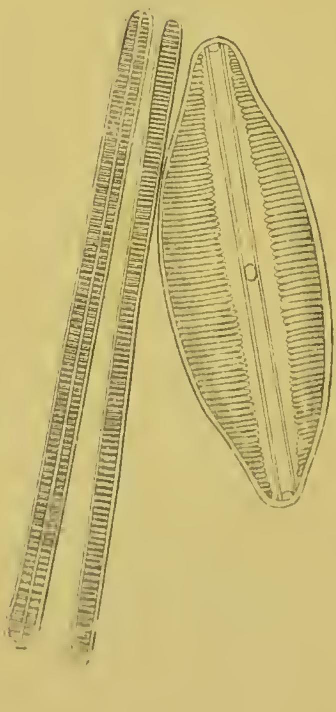


PLATE XIV.

Microscopic Objects.

Fig. 31.

Fig. 28.

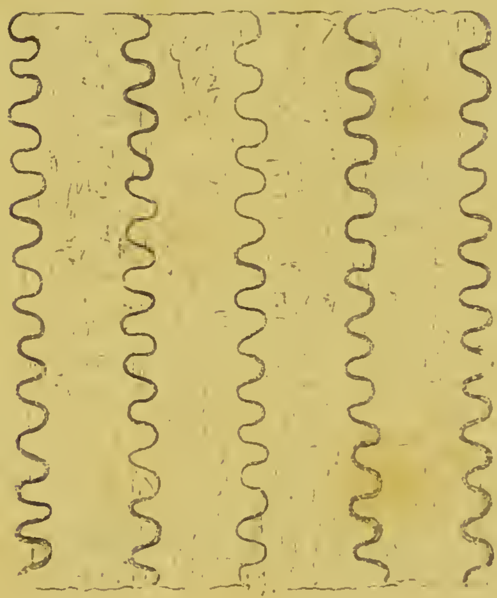
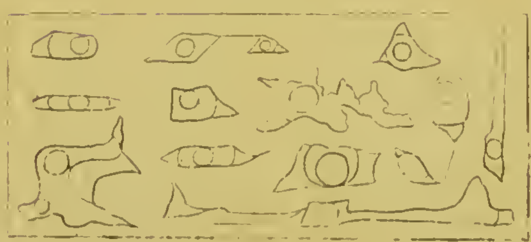


Fig. 30.

Fig. 29.



Nichol Edin.